

Mechanical Engineering Education

Mechanical Engineering Education

Edited by
J. Paulo Davim

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Preface

Mechanical engineering is currently being defined (nowadays) as a discipline “which involves the application of principles of physics, design, manufacturing and maintenance of mechanical systems”. Recently, the field of mechatronics has gained importance in mechanical engineering as well as in other modern disciplines. This book on mechanical engineering lays special emphasis on quality assurance and the improvement of higher education institutions, mechatronics education, and transfer of knowledge between university and industry. Chapter 1 discusses the quality assurance schemes applied to Greek Higher Education Institutions (GHEIs) in accordance with the specifications laid down by the European Higher Education Area (EHEA) and the European Standards and Guidelines. Chapter 2 covers mechatronics education. Chapter 3 contains information on the system of mechatronics education using multiple mobile robots with a behavior-based control approach. Finally, in Chapter 4, the transfer of knowledge between university and industry is discussed, which has the potential to bring great benefits to both partners; for example, in designing innovative solutions, in the optimal allocation of resources, in motivating students to new challenging tasks, and finally in integrating multidisciplinary teams from both university and industry.

This book can be used as course material for final-year undergraduate engineering students or for study as a discipline for mechanical engineering at the postgraduate level. It can also serve as a useful reference for academics, mechatronics researchers, mechanical and mechatronics engineers and professionals connected with mechatronics education.

The subject matter of this book should prove to be of interest to many institutes and universities throughout the world.

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J. PAULO DAVIM
Aveiro, Portugal
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Chapter 1

Quality Assurance in Greek HEIs: Convergence or Divergence with European Models?

This chapter discusses the quality assurance schemes applied to Greek Higher Education Institutions (GHEIs), in accordance with the context and specifications induced by the European Higher Education Area (EHEA) and the European Standards and Guidelines (ESG). Section 1.3 summarizes the quality management models with an emphasis on those applied to higher education, while section 1.4 focuses on quality assurance schemes in the EHEA. Section 1.5 examines the case of Greek HEIs.

1.1. Introduction

A core component of higher education reform is the systematic quality assurance and improvement of the Higher Education Institutions (HEIs). The “Communiqué of the Conference of Ministers Responsible for Higher Education” in Berlin on 19 September 2003 establishes that the quality

Chapter written by Nikolaos M. VAXEVANIDIS.

of higher education has “proven to be at the heart of the setting up of a European Higher Education Area”. Assuring quality in teaching and learning is no longer a matter only for the higher educational policy programs or broad international professional discussion. Quality development and assurance have for a long time played a central role in strategic higher educational planning and in the everyday work of HEIs [SPA 08].

In many countries and many cultures, the issue of quality management has been firmly on the agenda of HEIs for quite some time. Higher education for the masses and a growing climate of increased accountability are frequently cited as rationales for a greater emphasis on quality [ERI 95, BEC 06]. Other reasons include the greater expectations and diversity of students as consumers, their demand for increased flexibility in provision and increasing levels of competition within and across national borders. The role of HEIs in stimulating national economic growth and the value of international students to national economies, emphasize the need to ensure quality within Higher Education (HE). These forces demand that quality assurance processes are both rigorous and transparent, and that quality enhancement initiatives are firmly embedded in any quality management program.

This has led to the emergence of a debate on the applicability of quality management principles, methodologies and tools for the HE sector. A study of the literature on higher education indicates that a number of researchers support the non-applicability of those management theories, especially because they are derived from industry and have nothing to do with the higher education ethos [HAR 95; PRA 10]. Other authors have given a more balanced view on the subject, claiming that although HEIs are not companies, some of the basic principles and tools could be applied, as long as they were instruments at the service of

institutions and their governance and management boards, subject to the academic mission, goals and strategies of the institution [WIL 93, DIL 95, SPA 08].

Although this is an old debate, no firm conclusions have been arrived at so far. It seems, nevertheless, that in Europe, due to the developments on quality assurance schemes following the Bologna Declaration, HEIs are now being “forced” to implement internal quality assurance systems based on the European standards and guidelines (ESG); see [ROS 12].

1.2. Definitions and fundamentals

In quality management, it is vital to study the meaning of quality in the situation under examination. In the area of higher education, the concept of what constitutes quality has not been thoroughly addressed, although some interesting studies exist; for an overview see [LAG 04, VEN 07]. Furthermore, there is the vast field of general research into quality management in services. The extent to which this research is applicable to the higher education sector also needs to be analyzed.

There are various well-known definitions of quality. Crosby (1979) defines quality as “conformance to requirement” while Juran and Gryna (1980) define quality as “fitness for use”. Deming’s (1986) definition of quality as “a predictable degree of uniformity and dependability at low cost and suited to the market” is more concerned with quality in operation. Many organizations found that the old definition of quality – “the degree of conformance to a standard” – was too narrow, and have consequently started to use a new definition of quality in terms of “customer focus” [SPA 08].

As far as total quality management (TQM) is concerned, there are a number of researchers who have proposed

frameworks and/or models for quality improvements; it is not the scope of the present chapter to present them critically. In general, it is agreed that TQM consists of two main notions – continuous improvement and the tools and techniques/methods used. In general, TQM encompasses many management and business philosophies while its focus shifts, based on a scenario where TQM is applied. Whether it is in industry or in higher education, TQM philosophy revolves around the customer [SPA 08].

Quality in higher education is even more difficult to define than in most other sectors. Frazer [FRA 94] argues that a first important step would be to agree internationally on terms such as levels, standards, effectiveness and efficiency. Such agreement on basic factors is also an objective for the so-called “Bologna process” of integration currently taking place in Europe. Discussing quality in higher education, Harvey and Green [HAR 93] proposed five discrete but interrelated ways to think about quality:

- 1) *Quality as exceptional*. Quality is regarded in terms of excellence, which means something special or exceptional. High standards are exceeded.
- 2) *Quality as perfection or consistency*. The focus is on processes and specifications that are aimed to be perfectly met. Excellence, in this case, means “zero defects”, i.e. perfection.
- 3) *Quality as fitness for purpose*. Quality has meaning only in relation to the purpose of the product. In traditional quality management, the “fitness for purpose” notion was related to the customers; an idea originated by Juran. In higher education, however, a number of researchers view quality as “meeting customer requirements” to be problematic due to the contentiousness of the notion of “customer” and the difficulty for students for example to specify what is required.

4) *Quality as value for money*. Quality is equated with the levels of specifications and is directly related to costs.

5) *Quality as transformation*. The process should ideally bring about a qualitative change, a fundamental change of form, such as the phase transition when water transforms into ice as the temperature is lowered. This view can be found in the thinking of major Western philosophers, as well as in Eastern philosophies. In education, the transformation can take the form of enhancement and empowerment.

Next, in order to set the complete stage, some additional definitions are needed. *Quality assurance* is defined in the ISO 9000:2005 standards as “part of quality management focused on providing confidence that quality requirements will be fulfilled” while *quality management* is defined as “coordinated activities to direct and control an organization with regard to quality” [ISO 05]. Note that *quality assurance* has been defined most broadly in [GRA 09] as “...systematic management and assessment procedures adopted by a higher education institution or system to monitor performance and to ensure achievement of quality outputs or improved quality”. On the other hand, [SCH 04a] defines a quality assurance scheme or quality assurance system as “accreditation and evaluation systems together” by defining *accreditation* as “institutionalized and systematically implemented evaluation schemes that end in a formal summary judgment that leads to formal approval processes regarding the respective institution, degree type and/or program”. Within this concept, *accreditation* is the element of quality assurance schemes that set the standards for granting the “right to exist” within the system. In turn, *evaluation* activities are defined as “institutionalized and systematically implemented activities regarding the measurement, analysis and/or development of quality for institutions, degree-types and/or programs”.

The terms *assessment* and *evaluation* are often used synonymously, denoting both *means*, i.e. techniques, procedures, instruments and methods for measurement and analysis used to monitor performance and, *ends*, “to ensure achievement of quality outputs or improved quality”. *Accountability* is another term that has been associated with such a definition and denotes a *responsibility or answerability to external audiences* [GRA 09].

The linking of accreditation, evaluation or assessment and accountability in higher education Quality Assurance (QA) schemes causes considerable tension because of their historical, philosophical, political and social background. Understanding this background can help us, first, to appreciate how the quality assurance movement arrived at where it is today and, second, how development in the future should be guided; see for example [GRA 09, ROS 12].

1.3. Quality management models in HE

1.3.1. Overview

While there has been considerable interest in issues concerning how quality could be defined [HAR 93, SPA 08], in the design and relevance of various national quality assurance schemes in higher education [SCH 04b] as well as in the outcomes and effects of such quality assurance processes throughout the world [STE 08], the analysis of models or approaches of quality assurance at the institutional level is rarely addressed. In [BRO 07] a summary of research on quality management at the institutional level has been presented. It points out that the introduction of quality management concepts in higher education are mainly an externally-driven process related to increased demands for accountability and efficiency in the sector. They also found that much attention has been given to quality management models developed for business and

industry, and there is a concern that such models may add little to the improvement of teaching and learning, although they might have advantages for improving accountability.

The review indicates that a range of quality management models developed for industry have been adopted or proposed for adoption within HE institutions on a global basis. Internationally, the model most frequently drawn upon, see for example [MOT 97, CRU 03], is TQM defined as “a management approach of an organization, centered on quality, based on the participation of all its members and aiming at long run success through customer satisfaction and benefits to all members of the organization and to society” [WIN 03, SPA 08].

As the definition implies, TQM has the potential to encompass the quality perspectives of both external and internal stakeholders in an integrated manner. It thereby facilitates a comprehensive approach to quality management that will assure quality, as well as change and innovation. Other models that were tested emulate TQM and concentrate on developing systematic business processes that are required to achieve measurable quality outputs. For example, the balanced scorecard requires the identification of appropriate performance indicators, and the European Framework for Quality Management (EFQM), performance enablers and results. The one exception is SERVQUAL, a model that focuses on the assessment of quality solely from the consumer perspective. Table 1.1 identifies and defines the different models that have been applied internationally in HEIs. The application of these models within HEIs, have been summarized in [BEC 08, THA 12]. In a similar manner, a recent review paper, see [ROS 12], examines which of the several methodologies concerning quality management and improvement in organizations could also be implemented in HEIs and concludes that “the ISO 9000 standards, the

Balanced Scorecard and the EFQM excellence model deserve to be noticed due to their international recognition and previous validation”; see also [BEC 08].

Model	Description
ISO 9000 series	International standard for generic quality assurance systems. Concerned with continuous improvement through preventive action. Elements are customer quality and regulatory requirements, and efforts are made to enhance customer satisfaction and achieve continuous improvement.
TQM	A comprehensive management approach which requires contributions from all participants in the organization to work toward long-term benefits for those involved and society as a whole.
EFQM excellence model	Non-prescriptive framework that establishes nine criteria (divided between enablers and results), suitable for any organization to use to assess progress toward excellence.
M. Baldrige award	Based on a framework of performance excellence, which can be used by organizations to improve performance. Seven categories of criteria: leadership; strategic planning; customer and market focus; measurement, analysis and knowledge management; human resource focus; process management; and results.
SERVEQUAL	Instrument designed to measure consumer perceptions and expectations regarding quality of service in five dimensions: reliability, tangibles, responsiveness, assurance and empathy and identifying where gaps exist.
Balance scorecard	Performance/strategic management system that utilizes four measurement perspectives: financial, customer, internal process, and learning and growth.
Business process reengineering	System to enable redesign of business processes, systems and structures to achieve improved performance. It is concerned with change in five components: strategy, processes, technology, organization and culture.

Table 1.1. *Quality management models applied in HEIs*

Quality management in HEIs has been reviewed in a number of publications; see for example [HAR 95, BRE 00, PRA 10]. It is, in general, agreed that after the first wave of attempts to copy private-sector models in higher education, more attention has been directed toward the development of quality management models that would take into consideration the specific characteristics of HEIs.

Type 1 – Academic	Subject focus – knowledge and curricula Professorial authority Quality values vary across institutions
Type 2 – Managerial	Institutional focus – policies and procedures Managerial authority Quality values invariant across institutions
Type 3 – Pedagogic	People focus – skills and competencies Staff developers/educationalist influence Quality values invariant across institutions
Type 4 – Employment focus	Output focus – graduate standards/learning outcomes Employment/professional authority Quality values both variant and invariant across institutions

Table 1.2. *Categorization of quality management approaches for HEIs [BRE 00]*

An important framework for the taxonomy of quality management models is provided in [BRE 00]. According to this, the choice of an approach to quality management, as well as quality assessment, depends on “quality values” and “conceptions about what constitutes high quality in higher education”. Furthermore, the authors also differentiate between four main types of quality values stressing different focuses in approaches to quality management. These are *academic*, *managerial*, *pedagogic* and *employment focus* (see Table 1.2). In the first approach (academic), the focus is on the subject field, which is associated with professorial authority and where the academic values are of great

importance. “Conceptions” of quality are based on subject affiliation and vary across the institution, which has limited scope to define and assess quality. In essence, a quality management system should be decentralized, focusing on disciplinary characteristics and applying different quality standards. The managerial type has institutional policies and procedures as the main focus of assessment, underlying good management practices as the key factor of quality production. The characteristics of quality are considered as being “invariant” across the HEI. Here, centralization is seen as an essential characteristic of a quality management system, along with the coupling to institutional strategies and more coherent quality standards. The third type, described as “pedagogic”, focuses on people and pedagogical aspects of the process, i.e. teaching skills and methods, staff training and development. The characteristics of quality are regarded as invariant, across the whole institution. Unlike the first type, a lot of attention is paid here to a more standardized delivery process rather than the content in education. The “employment focus” approach focuses on learning outcomes, standards and output characteristics of graduates. This approach deals with customer requirements, where the customers are often regarded as being the employers of graduates. It tends to take into account both subject-specific and core characteristics of high quality education. Quality characteristics are seen as both invariant and variant, depending on a specific subject. The invariant dimensions could in this approach be linked to the generic skills often identified in national qualification frameworks.

These four categories offer a simple but efficient way of identifying the key characteristics and focus of a given quality management model and can be used as a heuristic tool for further analysis, although it should also be mentioned that the four dimensions may appear quite stylized and not capable of capturing the complexities of different approaches to quality management [PRA 10].

1.3.2. Implementation of ISO 9001 in HEIs

The ISO 9000 series standards emerged in 1987. These standards were subsequently revised in 1994, 2000 and 2008. Right from the release of these standards, the ISO 9000 certification has been implemented at a fast pace [SIN 06, VAX 06]. Today the ISO 9001:2008 standard sets the requirements for implementing a quality management system in an organization, independently of its dimension or type of activity, including educational institutions [HOY 09].

The primary benefit of obtaining an ISO 9001 certification and implementing the criteria of quality awards is to achieve global competitiveness by infusing a higher degree of quality in products, processes and services. A large number of industrial organizations have implemented the requirements of clauses and criteria of these quality models [SIN 06]. However, this kind of progress is not discernable in engineering educational institutions (EEIs).

The ISO 9001:2008 standard specifies the minimum requirements to set up a management system. It is organized in five main blocks: *quality management system*, *management responsibility*, *resource management*, *product realization*, and *measurement, analysis and improvement*; see Figure 1.1.

According to the ISO 9000:2005 standard, developing and implementing a quality management system include a succession of discrete phases that are as follows:

- Determining the needs and expectations of customers and other interested parties.
- Establishing a policy for quality and the organization's quality goals.

- Defining the processes and responsibilities needed to attain the quality goals defined.
- Determining and making available the resources needed to attain the quality goals defined.
- Establishing the methods to measure the efficiency and efficacy for each process.
- Applying these measures to determine the efficiency and efficacy in each process.
- Identifying the means to prevent non-conformities and eliminate their causes.
- Establishing and applying a process leading to the continuous improvement of the organization's quality management system.

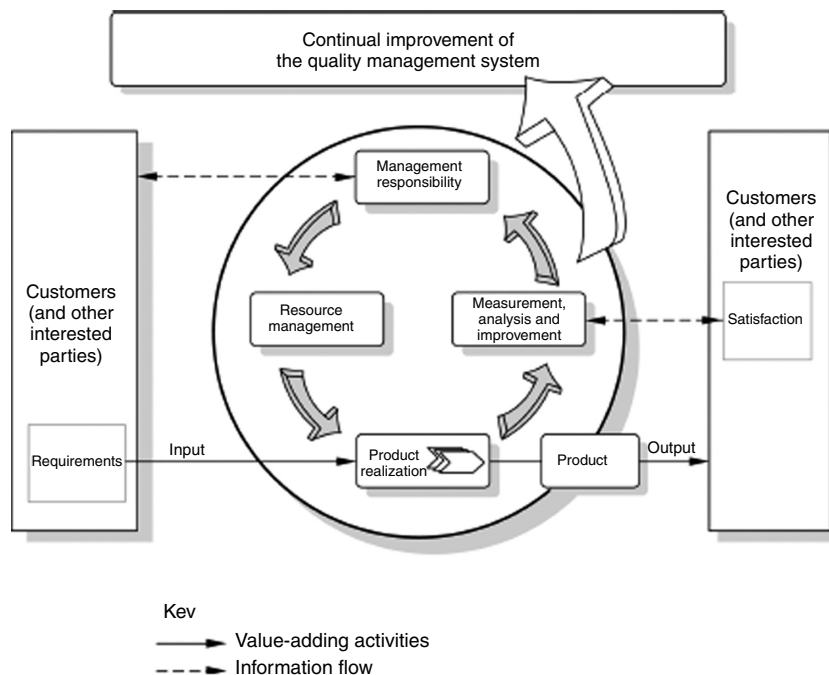


Figure 1.1. *The ISO 9001:2008 standard model
(adapted from ISO 9001:2008)*

A lot of criticism has emerged, concerning the application of this standard to HEIs, either because the “ISO approach entails too general a view of the ‘production process’ of higher education” or because it imposes a high degree of standardization in the process, which is incompatible with the nature of HEIs [ROS 12].

Earlier, in [KAR 98] it had been mentioned that certain universities and community colleges in Europe, Singapore and Canada have obtained an ISO 9000 certification. This publication listed as many as 13 benefits of obtaining an ISO 9000 registration in higher education, while high costs and a great amount of staff time were considered the main disadvantages. Similarities and differences between an ISO 9000 certification and accreditation requirements were also listed. Similar findings were also reported in [SAR 00]. However, as indicated in [THA 12] both papers have dealt with the earlier version of ISO 9000 series standards released in the year 1994; hence their contributions have become obsolete. Newer publications indicate that although the ISO 9000 series quality management system was designed for manufacturing, the ISO 9001 standard has also become a popular choice for educational systems worldwide [KAR 02, SIN 06, THO 06]. At the end of 2008, the service sector, including education, accounted for 40% of all ISO 9001 certificates [GAM 12]. In general, there is little published research about the implementation of ISO 9000 in educational institutions. The literature surrounding ISO implementation in education indicates that the application of ISO standards to education remains debatable, the implementation process is time-consuming and difficult and the subject is under-studied empirically [THO 06, PAP 10]. In [GAM 12], it has been pointed out that further research is necessary to assess the consequences of ISO 9000 implementation entirely in educational institutions, including an identification of the factors affecting its success. Moreover, it is indicated that the application of the ISO 9001

in higher education has been generically limited to the institutions' services and not to their core functions, namely teaching and learning (see [ROS 12]).

1.3.3. Implementation of EFQM model in HEIs

The quality award model most widely used in Europe has been developed by the European Foundation for Quality Management (EFQM). The EFQM was formed in 1988 by 14 leading European businesses organizations, and it encourages European firms to improve competitiveness through the use of TQM philosophy. The EFQM has provided a holistic model (termed "business excellence" or the "excellence model") to facilitate such a purpose. The model and the associated self-assessment process have given a new direction to the quality movement and have driven deep and lasting changes into participating organizations.

The EFQM excellence model was introduced at the beginning of 1992 as the framework for assessing organizations for the European Quality Award (EQA). It is now the most widely used organizational framework in Europe and has become the basis for the majority of national and regional Quality Awards [VAX 06, SAM 12].

The EFQM excellence model is a powerful tool that can be used in a number of different ways:

- as a tool for *self-assessment*;
- as a way to *benchmark* with other organizations;
- as a guide to identify areas for *improvement*;
- as the basis for a common *vocabulary* and a way of thinking;
- as a *structure* for the organization's management system;

– as a *learning opportunity* for stakeholders to view strengths and identify improvement opportunities.

The EFQM model is based on nine criteria. Five of these are “enablers” and four are “results”. The “enablers” criteria cover what an organization does. The “results” criteria cover what an organization achieves. “results” are caused by “enablers” and feedback from “results” help to improve “enablers” [SPA 08, EFQ 12]. In particular, the “enablers” are leadership, people, strategy, partnerships and resources, processes, products and services while the “results” are people results, customer results, society results and key results. The EFQM model is presented in diagram form in Figure 1.2.

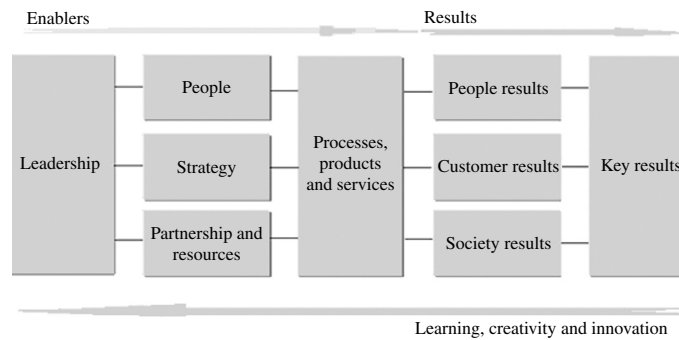


Figure 1.2. *EFQM excellence model [EFQ 12]*

The EFQM suggests a number of approaches for implementing the EFQM excellence model. However, it is not possible to point out a unique best approach to use it, because each implementation is organization specific. The use of the EFQM model in the public sector, and particularly in HEIs, has been significant. This is mainly because in the past few years there has been an increase in the pressure over public institutions to fulfill customer requirements through continuous improvement, as well as being a result of EFQM efforts in this area [HID 04, SAM 12].

Some additional information and milestones associated with the EFQM model in education are as follows [SAM 12]:

- In 2000, a university did reach the finalist category for the first time – Marmara University, Faculty of Engineering, Turkey.
- In 2001, for the first time a teaching institution won an award – St. Mary’s College, Northern Ireland.
- During the time period that ranged from 1992 to 2009, 13 teaching institutions reached the final phase of the EQA, including three universities.

1.4. European focus on quality in HE: a historical perspective

1.4.1. *Historical perspective*

Accreditation and quality assurance processes in Europe have their roots in the 1950s, when several initiatives at regional and national levels were carried out in the form of educational audits, intended to assess pedagogical skills in higher education [IRA 00]. The establishment of the European Federation of National Engineering Associations in 1951 was an important initiative intended to foster a common accreditation approach for engineering education in Europe.

Note that quality assurance of higher education in the United States, based on a scheme of professional authority gained through experience, began in the late 1800s while QA in engineering and technology programs began as a voluntary effort organized by the Accreditation Board for Engineering and Technology (ABET, Inc.) in 1936 [GRA 09]. However, as indicated in [AUG 07], “the word accreditation, used in the United States since the 1930s, did not find its way into European specialized literature and official

documents until very recently, but since then it has rapidly become a catchword”.

From the 1980s onward, the development of quality assurance in Europe was fast. A number of reasons contributed to the establishment of quality assurance or accreditation agencies in the mid-1980s as was the case in the United Kingdom, in France (1984) and in the Netherlands (1986). During the 1990s, evaluation and accreditation agencies were established not only in most of the former Eastern Bloc countries (Czech Republic in 1990; Slovakia in 1990; Hungary in 1993; Latvia in 1994; Estonia in 1997) but also in most of the European Union countries (Denmark in 1992; Sweden in 1995; Finland in 1996). The Mediterranean countries were quite late in developing quality assurance national agencies, such as Spain (ANECA in 2002), Greece (HQAA in 2005) and Turkey (YÖDEK in 2005) [ASD 09].

Moreover, with the internationalization of higher education, the emergence of new providers and new methods of delivering higher education, and the need to evaluate their quality, as well as the inclusion of higher education services within the GATS negotiations, and the development of inter-university cooperation addressed the need for setting standards and criteria at an international level [SAD 00]. As a result, the quality assurance schemes linked with the recognition of degrees became a crucial issue within the fora of international organizations such as the Council of Europe, OECD and UNESCO. The most important international attempts to address the need for a consensus on quality provisions among countries, international players, HEIs and stakeholders in cross-border higher education are summarized in [SAD 00, RAU 05, ASD 09].

During the 1990s, the evaluation of higher educational systems was placed at the center of the European Union initiatives. On the initiative of the Dutch European Union’s

Presidency (1991), the European Pilot Project for Evaluating Quality in Higher Education (1994–1995), in which a total of 46 institutions participated, was introduced. The Council's Recommendation of 24 September 1998 (98/561/EC) encouraged the European Union member-states to establish national quality assurance systems for higher education, based on the four-stage model; this included the establishment of an independent agency, internal and external institutional evaluation procedures, the involvement of various stakeholders and the publications of the results [ENQ 03]. The European Network for Quality Assurance in higher education (ENQA) was established in 2000 and consisted of independent bodies and quality assurance agencies recognized by competent public authorities of the EU member-states, the EEA/EFTA countries and the countries that participate in the EU programs on Education and Training. Nowadays, ENQA is open to quality assurance agencies coming from the Member-States of the Bologna process [ASD 09].

The Bologna process gave new impetus to the development of national quality assurance systems. “Promotion of European co-operation in quality assurance with a view to developing comparable criteria and methodologies” was set as the fifth axis of the collaboration between the 29 founding Member States of the process [BOL 99]. In Prague, on 19 May 2001, the Ministers “encouraged closer cooperation between recognition and quality assurance networks” and “they emphasized the necessity of close European cooperation and mutual trust in and acceptance of national quality assurance systems”, as well as the need for cooperation between national agencies, HEIs and ENQA to “collaborate in establishing a common framework of reference and to disseminate best practice”. As a result, bilateral and regional cooperation on quality assurance issues was developed after Prague and various networks were established; see [ASD 09, KAV 11] for details.

The mid-term goal that was set up in the Berlin Ministerial Meeting (19 September 2003), concerning quality assurance, gave an additional push to those countries that were behind time. The ministers agreed that by 2005 national quality assurance systems would include the following:

- 1) Definition of the responsibilities of the bodies and the institutions involved; evaluation of programs or institutions, including internal assessment, external review.
- 2) Participation of students and the publication of results.
- 3) A system of accreditation, certification or comparable procedures.
- 4) International participation, cooperation and networking [BER 03].

Taking one step further, 45 countries adopted the *European Standards and Guidelines for Quality Assurance* in EHEA as proposed by ENQA and its partners in Bergen (2005) (EUA, EURASHE and ESIB), while the European Quality Assurance Register for Higher Education (EQAR) was approved in London (2007) [BER 05, ASD 09].

The ESG for quality assurance are a set of standards, procedures and guidelines that HEIs and accredited agencies (the ones responsible for assessing and accrediting higher educational programs and institutions) should follow to implement, assess and accredit quality assurance systems in the EHEA; see [ESG 09]. They constitute a first step to the establishment of a widely shared set of underpinning values, expectations and good practices in relation to quality and its assurance, by institutions and agencies across the EHEA, aiming at providing a source of assistance and guidance to both HEIs and agencies, while contributing to a common frame of reference. The ESG are divided into three parts: Part 1, referring to standards and guidelines for internal

quality assurance within HEIs; Part 2, referring to standards for the external quality assurance of higher education and Part 3, referring to standards for external quality assurance agencies [ROS 12].

A fruitful outcome of the Berlin Communiqué was the introduction of the so-called “stocktaking exercise”, which would record the progress achieved in the three priority action lines including quality assurance, i.e. the establishment and the implementation of national quality assurance systems [BER 03]. Representatives of countries, as well as, the European Commission, EUA, the European Student’s Union (ESU) and Eurydice were involved in this exercise. Scorecards were set up according to certain criteria and benchmarks, following the traffic lights performance system; green stands for excellent (5), light green for very good (4), yellow for good performance (3), orange for some progress (2) and red for little progress (1) [BOL 05].

The scorecard criteria concerning quality assurance were as follows:

- 1) Stage of development of the quality assurance system.
- 2) Key elements of evaluation systems.
- 3) Level of participation of students.
- 4) Level of international participation, cooperation and networking.

As might be expected, the traffic lights scorecards that were issued to country representatives in March 2005 for comments or additional justification exerted considerable pressure on the countries, which in several cases tried to improve their national status. Traffic light scorecards, actually, were a visual representation of the achievements or the delays for each country and respectively an assessment of the national ministries’ accomplishment within the two-year period. Each country’s scorecard would

have two-level recipients: peers and the European Commission at the European level, as well as, the domestic political elite, interest groups and the public opinion at national level [ASD 09].

Part of the results of the “stocktaking exercise” is presented in Table 1.3; the gap between North Europe and Southern Europe, at that time, as far as the development of quality assurance system in HEIs is concerned, is evident.

Stocktaking Report (2005) Criterion 1: Stage of development of quality assurance system.			
Finland	5	Greece	3
Sweden	5	Italy	3
Estonia	5	Turkey	2
Germany	5	Slovenia	3
Denmark	5	Bulgaria	3
United Kingdom	5	Romania	3
Iceland	5	Serbia	3
Ireland	5	Bosnia-Herzegovina	3

Table 1.3. *Part of the Bologna scorecard summary [BOL 05]*

The development of QA in Europe is discussed in detail in [SCH 04a, AMA 10]; therefore, it is not considered here, further. However, if a comparison is made between state approval and accreditation schemes, a profound movement toward accreditation is identified. All recently implemented quality systems are based on accreditation, while old systems based on quality assessment were replaced by accreditation systems under the aegis of independent accreditation agencies. A key contributor to this movement has been the Bologna declaration (as indicated above), signed by 29 European countries in 1999 and the process that followed [ROS 12].

The ESG establish seven standards for quality assurance within HEIs, complemented with guidelines for

their implementation. These standards and guidelines are reproduced below [ESG 09].

1.4.1.1. *Policy and procedures for quality assurance*

1.4.1.1.1. Standard

Institutions should have a policy and associated procedures for the assurance of the quality and standards of their programs and awards. They should also commit themselves explicitly to the development of a culture, which recognizes the importance of quality, and quality assurance, in their work. To achieve this, institutions should develop and implement a strategy for the continuous enhancement of quality.

The strategy, policy and procedures should have a formal status and be publicly available. They should also include a role for students and other stakeholders.

1.4.1.1.2. Guidelines

Formal policies and procedures provide a framework within which HEIs can develop and monitor the effectiveness of their quality assurance systems. They also help to provide public confidence in institutional autonomy. Policies contain the statements of intentions and the principal means by which these will be achieved. Procedural guidance can give more detailed information about the ways in which the policy is implemented and provides a useful reference point for those who need to know about the practical aspects of carrying out the procedures.

The policy statement is expected to include:

- the relationship between teaching and research in the institution;
- the institution's strategy for quality and standards;

- the organization of the quality assurance system;
- the responsibilities of departments, schools, faculties and other organizational;
- units and individuals for the assurance of quality;
- the involvement of students in quality assurance;
- the ways in which the policy is implemented, monitored and revised.

The realization of the EHEA depends crucially, on a commitment at all levels of an institution to ensure that its programs have clear and explicit intended outcomes; that its staff are ready, willing and able to provide teaching and learner support that will help its students achieve those outcomes and that there is full, timely and tangible recognition of the contribution to its work by those of its staff, who demonstrate particular excellence, expertise and dedication. All HEIs should aspire to improve and enhance the education that they offer their students.

1.4.1.2. Approval, monitoring and periodic review of programs and awards

1.4.1.2.1. Standard

Institutions should have formal mechanisms for the approval, periodic review and monitoring of their programs and awards.

1.4.1.2.2. Guidelines

The confidence of students and other stakeholders in higher education is more likely to be established and maintained through effective quality assurance activities, which ensure that programs are well-designed, regularly monitored and periodically reviewed, thereby, securing their continuing relevance and currency.

The quality assurance of programs and awards are expected to include:

- development and publication of explicit intended learning outcomes;
- careful attention to curriculum and program design and content;
- specific needs of different modes of delivery (e.g. full time, part-time, distance learning, e-learning) and types of higher education (e.g. academic, vocational, professional);
- availability of appropriate learning resources;
- formal program approval procedures by a body other than that teaching the program;
- monitoring of the progress and achievements of students;
- regular periodic reviews of programs (including external panel members)
- regular feedback from employers, labor market representatives and other relevant organizations;
- participation of students in quality assurance activities.

1.4.1.3. *Assessment of students*

1.4.1.3.1. Standard

Students should be assessed using published criteria, regulations and procedures, which are applied consistently.

1.4.1.3.2. Guidelines

The assessment of students is one of the most important elements of higher education. The outcomes of assessment have a profound effect on the future careers of students. It is, therefore, important that assessment is carried out professionally at all times and that it takes into account the

extensive knowledge that exists about testing and examination processes. Assessment also provides valuable information for institutions about the effectiveness of teaching and support for learners.

Student assessment procedures are expected to

- be designed to measure the achievement of the intended learning outcomes and other program objectives;
- be appropriate for their purpose, whether diagnostic, formative or summative;
- have clear and published criteria for marking;
- be undertaken by people who understand the role of assessment in the progression of students toward the achievement of the knowledge and skills associated with their intended qualification;
- where possible, not rely on the judgments of single examiners;
- take account of all the possible consequences of examination regulations;
- have clear regulations covering a student's absence, illness and other mitigating;
- circumstances ensure that assessments are conducted securely in accordance with the institution's stated procedures;
- be subject to administrative verification checks to ensure the accuracy of the procedures.

In addition, students should be clearly informed about the assessment strategy being used for their program, what examinations or other assessment methods they will be subject to, what will be expected of them and the criteria that will be applied to the assessment of their performance.

1.4.1.4. *Quality assurance of teaching staff*

1.4.1.4.1. Standard

Institutions should have ways of satisfactorily maintaining that staff involved with the teaching of students are qualified and competent to do so. They should be available to those undertaking external reviews and commented upon in reports.

1.4.1.4.2. Guidelines

Teachers are the single most important learning resource available to most students. It is important that those who teach have a full knowledge and understanding of the subject they are teaching, have the necessary skills and experience to transmit their knowledge and understanding effectively to students in a range of teaching contexts and can access feedback on their own performance. Institutions should ensure that their staff recruitment and appointment procedures include the means of making certain that all new staff have at least the minimum necessary level of competence. Teaching staff should be given opportunities to develop and extend their teaching capacity and should be encouraged to value their skills. Institutions should provide poor teachers with opportunities to improve their skills to an acceptable level and should have the means to remove them from their teaching duties if they continue to be demonstrably ineffective.

1.4.1.5. *Learning resources and student support*

1.4.1.5.1. Standard

Institutions should ensure that the resources available for the support of student learning are adequate and appropriate for each program offered.

1.4.1.5.2. Guidelines

In addition to their teachers, students rely on a range of resources to assist their learning. These vary from physical resources such as libraries or computing facilities, to human support in the form of tutors, counselors and other advisers. Learning resources and other support mechanisms should be readily accessible to students, designed with their needs in mind and responsive to feedback from those who use the services provided. Institutions should routinely monitor, review and improve the effectiveness of the support services available to their students.

1.4.1.6. *Information systems*

1.4.1.6.1. Standard

Institutions should ensure that they collect, analyze and use relevant information for the effective management of their programs of study and other activities.

1.4.1.6.2. Guidelines

Institutional self-knowledge is the starting point for effective quality assurance. It is important that institutions have the means of collecting and analyzing information about their own activities. Without this, they will not know what is working well and what needs attention, or the results of innovative practices.

The quality-related information systems required by individual institutions will depend to some extent on local circumstances, but it is at least expected to cover:

- the progression and success rates of students;
- the employability of graduates;
- the students' satisfaction with their programs;
- the effectiveness of teachers;
- the profile of the student population;

- the learning resources available and their costs;
- the institution's own key performance indicators.

There is also value in institutions comparing themselves with other similar organizations within the EHEA and beyond. This allows them to extend the range of their self-knowledge and to access possible ways of improving their own performance.

1.4.1.7. Public information

1.4.1.7.1. Standard

Institutions should regularly publish up-to-date, impartial and objective information, both quantitative and qualitative, about the programs and awards they are offering.

1.4.1.7.2. Guidelines

For a fulfillment of their public role, HEIs have a responsibility to provide information about the programs they are offering, the intended learning outcomes of these, the qualifications they award, the teaching, learning and assessment procedures used and the learning opportunities available to their students. Published information might also include the views and employment destinations of past students and the profile of the current student population. This information should be accurate, impartial, objective and readily accessible and should not be used simply as a marketing opportunity. The institution should verify that it meets its own expectations with respect to impartiality and objectivity.

1.4.2. ESG standards versus typical quality systems

The ESG standards are definitely a European outcome, designed for implementation in EHEA. It is interesting, in the light of globalization, to examine how these standards fit

and/or complement the universal, market-oriented quality models described in section 1.3.1.

By comparing the paragraphs and clauses of ENQA standards with the corresponding paragraphs in the ISO 9000 series, a number of similarities arise. This comparison is summarized in Table 1.4.

Bologna process	ISO 9001:2008 standard
Establish the EHEA and clearly define the position and role of each higher educational institution in it.	Define the vision and mission of a higher educational institution, as well as the quality policy.
Assure the ability of students. Lecturing and administrative personnel through compatible curriculum and clear definition of inputs, outputs and mutual relations inside an institution aiming their mutual recognition.	Define the key and other own processes, their inputs, outputs and mutual relations inside the higher educational institution and related to the surrounding.
Put in agreement the standards and outputs of higher educational institutions aiming for their mutual recognition.	Define the goals of quality plan, their realization and continuously re-examine them.
Assure corresponding resources to realize the principles of the Bologna process.	Assure necessary resources to realize defined goals and processes.
Define and establish the obligations, responsibilities and rules of the behavior of all participants in higher education in a way of corresponding curriculum and of the credit system (ECTS) of evaluation, as well as corresponding models of following the progress of the students, lecturing and administrative personnel.	Define and establish the competences, responsibilities and rules of behavior of all participants inside each identified process in a way of corresponding documentation.

Table 1.4. *Comparison of ESG standards with ISO 9001:2008 requirements*

Assure equal standards, easily understandable and comparable diplomas, to realize pass ability and equilibrate quality of higher educational system.	Establish a system of collecting the information from the process and from the service users, as well as adequate methods of satisfaction measurement, aiming at continuous improvement of higher educational activity.
Assure and promote whole life learning.	Plan and perform continuous qualifying and additional education with the proof of their realization.
Accreditation of curricula and programs and higher educational institutions.	Certify the system of the quality management.

Table 1.4. (Continued) Comparison of ESG standards with ISO 9001:2008 requirements

A study of the ISO 9001:2008 requirements indicates that their implementation will answer to the ESG. “Addressing management responsibility” will lead to the implementation of *policy and procedures for quality assurance*, while the *approval, monitoring and periodic review of programs and awards* and the *assessment of students* are covered under the “realization of the product”. When implementing the “resource management” requirements, the *quality assurance of teaching staff* and the *learning resources and student support* standards are addressed. Finally the requirements put under “measurement, analysis and improvement” allow for the implementation of the *information systems* and *public information* standards. The idea underlying the ISO 9001:2008 standard is that there is the need to continuously improve an organization’s quality management system, based on the application of the PDCA (plan–do–check–act) cycle, that contributes to establish a link between the seven standards of ESG presented above, allowing for the implementation in the HEIs of a quality assurance system with a truly developmental character [ROS 12].

Similarly, a considerable number of similarities can be identified between the EFQM excellence model and the ESG standards. By analyzing the EFQM criteria, it is evident that they cover the standards for quality assurance predicted under [ESG 09]: *Policy and procedures for quality assurance* is addressed under the “Leadership and Strategy” criterion; *approval, monitoring and periodic review of programs and awards and assessment of students* under the “Processes, Products and Services” criterion; *quality assurance of teaching staff* under the “People” criterion; *learning resources and student support* is covered by the “Resources and Partnerships” criterion and finally both the *information systems* and the *public information* standards may be addressed through the different enablers and results criteria, depending on an institution’s local circumstances [ROS 07, ROS 12].

1.4.3. Accreditation of engineering education

Challenged by globalization (especially the General Agreement on Trade in Services, GATS) and by European developments (the Bologna process), program accreditation was introduced in EHEA as a new form of quality assurance. Other, sometimes similar, initiatives are found in other countries and at the international level [WES 03].

The literature dealing with accreditation in engineering education was reviewed recently in [GAM 12, THA 12]. The accreditation process in engineering education was initiated by the Accreditation Board for Engineering and Technology (ABET) in the United States, in 1932 [PAT 07]. After that, the European Federation of National Engineering Association was established in the year 1951; see also section 1.4.1. Another important development in the accreditation scenario

was the Bologna declaration of 1999 in Europe. As a result of this, the declaration, integration and mobility of engineers within Europe were facilitated [LUC 08].

In accreditation schemes, two relative terms are usually referred to: “General accreditation” and “engineering accreditation”. According to [PRA 05], the difference between them is that general accreditation is applied to the entire institution, whereas engineering accreditation is applied to specified engineering educational programs. Moreover, it is agreed, in general, that, accreditation serves two purposes. The first purpose is to enable the engineering undergraduate, postgraduate and PhD scholars to achieve mobility throughout the world. This is achievable if all the EEIs in the world are accredited by a commonly agreed standard and agency. The second purpose of accreditation is to achieve quality assurance and continuous quality improvement by the EEIs; a common objective of ISO 9001:2008 and ESG too. Based on information collected in [THA 12], it is evident that to achieve the global competitiveness and continuous quality improvement in engineering education, the majority of engineering HEIs tend to adopt ABET criteria. Initiatives such as the so-called “Washington accord” contribute significantly toward the same result; see also [PRA 05, THA 12].

For many decision-makers in European higher education, accreditation seemed to be the answer to the Bologna challenge. Judging on the basis of its sudden popularity after June 1999, there was not much of a survey of alternative policy options. A final argument in favor of accreditation is that it gives better consumer protection than the traditional Western European quality assessment does because a fixed quality threshold is established under which accreditation is denied [WES 03].

1.5. Quality assurance in Greece: a long and winding road

1.5.1. *Higher education in Greece*

Issues concerning the structure and operation of Greek higher education are presented in a number of recent publications; see for example [KYR 08, ASD 09, KIP 11, PAP 11].

Higher education in Greece is provided, according to the Constitution, by self-governed, legal entities under public law (Article 16 par. 5), which are supervised by the Ministry of National Education and Religious Affairs¹ (renamed recently M. of Education, Lifelong learning and Religious Affairs). Establishment of private HEIs is strictly forbidden (Article 16, par. 8).

The first Greek university (called “Hellenic University of Otto”) was founded in Athens in 1837. In 1873, the National Technical University was established, also in Athens. Following the turn of the century, other universities were established all across Greece. The great expansion of Greek higher education started during the 1970s, while from the mid-1980s, up till today, it has developed according to a regional approach. This means that universities and technological educational institutions were founded within a region and their schools or faculties or departments were spread in the capitals of the prefectures or other big cities.

Higher education comprises two parallel sectors: the university and the technological sector. Nowadays, 18 universities, two technical universities, the International Hellenic University, the Hellenic Open University and the School of Fine Arts compose the university sector and 15 Technological Education Institutions (TEI), as well as

¹ We use the term MoE (Ministry of Education) in the text for referring to this Ministry, irrespectively of its official name.

the School of Pedagogical and Technological Education (ASPETE) compose the technological sector. Note that until 2001, higher education included only the universities and not the TEIs, which were considered as professional institutions (polytechnics). HEIs consist of schools or faculties, departments and sections. A department is the autonomous educational unit entitled to award degrees [KYR 08, PAP 11]. In 2003, there were 240 university departments and 170 departments at the TEIs, a number that has increased by 43% over the period 1993–2003. The Ministry of Education is responsible for the approval of new institutions and new departments. However, the development of the corresponding study program is the responsibility of the institution [BIL 04]. Around 70.3% of the Lyceum graduates were admitted to higher education in 2008. Still, the demand is so high that Greece is an exporter of students to the United Kingdom, Germany, Italy, France and the United States [ASD 09].

There are three levels of study in Greek universities. The first is the undergraduate level, which leads to the basic degree, called “diploma”. The length of studies at this level varies from four to six years. Studies in medicine last for six years, whereas engineering, agriculture, dentistry and pharmacy, fine arts and music last for five years. Studies in all other fields last for four years.

Postgraduate studies are divided into two levels. The lower level is of one year’s duration in most cases and leads to the equivalent of a Master’s degree. In 1993, there were 53 postgraduate programs in universities, 111 in 1995 and 212 in 2000. This number exceeded 500, for all HEIs, in 2010. The higher level is the doctorate level and it lasts for at least three years.

Studies in the TEIs last for three-and-a-half to four years. Graduates have access to postgraduate studies, which are offered exclusively by the universities or a

collaboration scheme between a TEI and an accredited HEI from EHEA [BIL 04].

The higher educational system is public funded, based on the notion that “Education constitutes a basic mission of the State” (Greek Constitution, Article 16 par. 2). Study programs, with the exception of the programs of the Open University and the majority of the postgraduate programs, are free of charge and students enjoy several benefits (healthcare, free text books, scholarships, interest-free loans, free accommodation and board or a housing grant, depending on their income, reduced price tickets for transportations, cinemas, etc.). Professors, according to the Constitution, are public functionaries while the administrative staff of HEIs are civil employees.

The main teaching staff at universities in Greece in the last seven years grew from 7,258 in the academic year 1996–1997 to 9,776 in the academic year 2002–2003. In the academic year 1999–2000, 128,976 students were active at the universities. This gives a ratio of main teaching staff to students of about 1/16. In the academic year 2000–2001, 1,48,772 were active students at the universities, bringing the ratio down to 1/17, while in the academic year 2007–2008 this ratio was 1/16.5 [ADI 11].

At the TEIs, the main teaching staff numbers grew slightly over seven years, from 2,201 (1996–1997) to 2,302 in 2002–2003. With 79,102 active students in the academic year 1999–2000, the ratio of main teaching staff to students was 1/34. In the academic year 2000–2001, when 86,659 students were active, it dropped to 1/38. From the published data, see [ADI 09], the ratio is further decreasing; it was 1/53 for the academic year 2007–2008. Worth mentioning here is that in TEIs there is an extra number of teaching staff who are contractual and part-time teachers.

1.5.2. Greek HEI quality assurance system

Attempts made to introduce evaluation and/or quality assurance procedures at an institutional and/or departmental level in Greek HEIs have been reviewed in a number of recent publications; see [BIL 04, ASD 09, KAV 11, PAP 11].

The first law that enacted evaluation processes for every activity of a HEI was voted in 1992 by a conservative government. The 24th article of Law (Law 2083/1992) entitled “Evaluation of activities of Higher Education Institutions” promoted the enactment of an evaluation system for Greek universities. The legislator settled that in the evaluation should “*be taken under consideration the official planning of each Higher Education Institution (HEI)*”. It has been mentioned in the second article of the Law that the Senate has the responsibility for the preparation of the official planning of the university. The Law also established a connection between the results of the evaluation process with the extra public funding of the university. The legislator regulated the creation of an “Evaluation Committee” determining its composition. The evaluation method, the criteria and indicators were not determined, although the Law forecast the procedure under which the research for the best international practices would take place [BIL 04]. The Law was treated from both the opposition political parties and universities as an attempt from the MoE to control universities and was not actually implemented [ASD 09].

Despite the strong resistance against any national evaluation framework, Greek universities and TEIs have participated in various international evaluation projects since the mid-1990s. However, this participation has not been sufficient for the development of a quality culture [ASD 09, KAV 11].

Greece was a signatory country of the Bologna Declaration (1999). Nevertheless, the Declaration did not receive the appropriate approval, especially from the universities. The controversial issue was the reference to the three-year minimum duration of the first cycle, since most of the universities' first-cycle study programs last four years, those of technical universities' last five years and those of medical schools' last six years. The three-year Bologna bachelors' programs corresponded to those of the TEIs which, at that time, did not belong to higher education. Note that TEIs were recognized as HEIs by the Law 2916/2001, without any previous evaluation, a fact that caused additional strong reactions from the universities.

The Law 3374/2005 (the draft of which entered Greek Parliament before the Bergen Ministerial Conference) introduced a national quality assurance system in higher education, according to the *ESG* and established the European Credit Transfer System (ECTS) and the Diploma Supplement. It ensured the independent, objective and transparent function of the national system, which included the main elements of the four-stage model, i.e. internal and external evaluation processes, publication of the report and international participation, as well as a peer review for the quality assurance agency. The law clearly stated that the quality assurance system would be both an improvement and information tool and not a compliance one. A brief account of the opinions expressed by the various political parties during the discussion of the law in Greek Parliament is given in [KAV 11] and therefore it is not presented here.

The ECTS, as it is referred above, was also established under Law 3374/2005, with the objective of evaluating the study program undertaken by students and recognizing the students' achievements during their period of study at a European university. The system of transfer and accumulation of units is already in use at universities in EU

member countries at both the undergraduate and graduate levels. The system is based on the rule that 60 credit units represent one academic year's workload for a full-time student. That is, 30 credit units per semester or 20 units per trimester. In addition, the *Addendum of Degree* was established, which is an explanatory document that will be attached to the title of studies (degree). The document's purpose is to provide comprehensive information on the studies and the exact content of the studies undertaken by graduates [BOU 09].

The approval of the law caused reactions against universities by professors and student unions, on the other hand, it was supported by all the TEIs, who declared their willingness to be evaluated. They considered the evaluation as an opportunity to upgrade their status and to gain the competence to organize and operate postgraduate programs independently; see [ASD 09]. QA Law only became an active law (policy) in 2007.

According to the Law 3374/2005, the main goal of the Greek quality assurance system is to establish an integrated approach to record, comprehend, evaluate systematically and improve the activity and tasks of all HEIs regarding their mission and their profile. The quality of teaching and research, study programs and all other services provided by HEIs are assessed by internal and external procedures, using objective indicators and standards to note their achievements and also to trace their weaknesses in such a way that they can be treated accordingly, with state support. Evaluation may concern HEIs as a whole, or particular faculties or departments, or particular independent units.

The law establishes an independent administrative authority called the Hellenic Quality Assurance Agency for higher education (HQAA or ADIP in Greek) located in Athens, which coordinates the evaluation processes at a national level. HQAA consists of 15 members, including

professors nominated by the rectors and presidents of TEI conferences, student representatives, researchers and social partners. The HQAA is the body responsible for the smooth operation of the national quality assurance system. It supports the HEIs during their self-evaluation processes and keeps the competent bodies of the state and HEIs up to date concerning the international trends and developments in quality assurance. HQAA compiles, keeps and revises a register of Greek and foreign experts and specialists; it organizes the external evaluation process, keeps an archive containing all evaluation reports and annually submits a general report to the Parliament. In this report, it makes suggestions and recommendations regarding the improvement of the national higher educational system. Last but not least, HQAA is also placed under a self-evaluation and peer-review process. Since September 2007, HQAA has been an associated member of ENQA [ASD 09].

The “heart” of the Law 3374/2005 is article 3 entitled “Evaluation criteria and indices”. These criteria and indices refer to the following four axes:

- 1) *Quality of tuition*: the efficiency of the teaching staff, the quality of the teaching process, the organization and implementation of the teaching tasks, teaching aids, media and infrastructures, the use of new technologies, the ratio of students to teachers and cooperation between teachers and students, the level and timeliness of the knowledge provided, the interrelation between research and teaching, the mobility of teaching staff and students.

- 2) *Quality of the research work*: the fostering of research in the framework of the academic unit, the scientific publications, research infrastructures, research programs, the effectiveness of the research work, the originality of the research, the acknowledgment of the research by third parties, the research partnerships, research distinctions and

awards, as well as the participation of students in the research.

3) *Quality of curricula*: the degree to which the curriculum meets the academic unit's objectives and society's demands, the cohesion and applicability of the curriculum, the coordination of the syllabus, the rational organization of the educational institutions, the examination system, the support by available educational infrastructure.

4) *Quality of other services*: the effectiveness of the administrative services, student welfare services, all kinds of infrastructures, the use of new technologies, the transparency and efficiency in the management of financial resources, as well as in the use of infrastructure and equipment, cooperation with other educational or research institutions, whether Greek or foreign, and with the community.

It should be noted that according to this Law, "the evaluation procedure taking place pursuant to the provisions of this law may not be replaced by other forms of quality assurance and improvement which are not anticipated hereby".

Each HEI in Greece is required under the Law 3374/2005 to establish an institutional QA unit (MODIP), to coordinate and support evaluation procedures. This unit is to be chaired by the HEI's vice-rector or vice-president and involves representatives of the academic and administrative staff. Additionally, each academic department appoints an Internal Evaluation Committee (OMEA) to collect data, documents and information to develop the department's self-assessment report. From the academic year 2009–2010, the "new" MoE requires all HEIs to submit a self-assessment report and to invite external evaluators for review. Without adoption of evaluation, departments will face problems in relation to their operation (funding and human resources) [PAP 11].

Following the general guidelines of HQAA, the QA process at TEIL works on a four-year cycle, as illustrated in Figure 1.3. The internal processes lead to the compilation of self-evaluation reports, while the HQAA controls the external review process (i.e. maintaining registry of reviewers, setting up the review teams and compiling the external review reports).

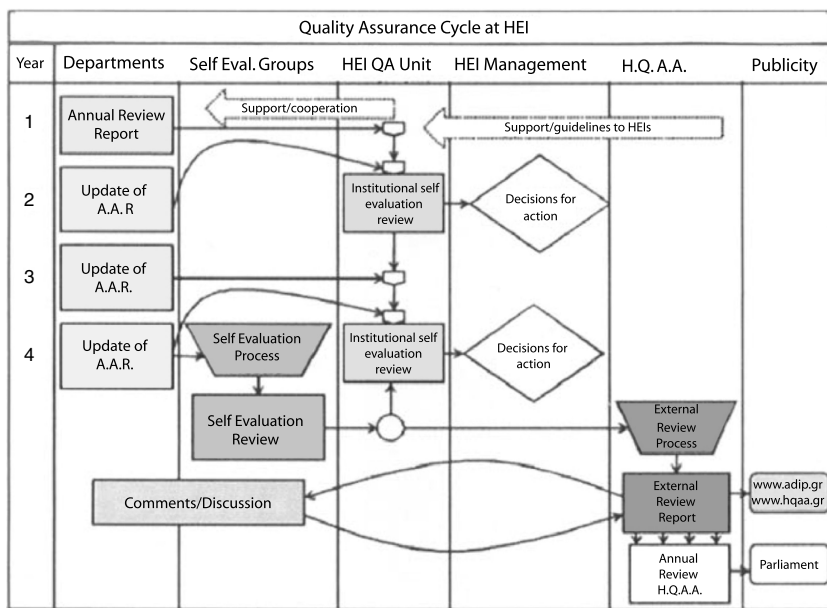


Figure 1.3. *Typical Quality Assurance cycle of an HEI (proposed by the HQAA)*

According to the latest published report from ADIP [ADI 12], the internal self-evaluation of Greek HEIs has been completed to a level of 85%. 285 university departments and 186 TEI departments have submitted their internal evaluation with only 72 departments remaining to submit the required report. As far as the progress of external evaluation is concerned, Table 1.5 summarizes the situation up to now (06/2012).

Year	Universities	TEIs	Total
2008	2	3	5
2009	–	–	–
2010	19	19	38
2011	48	33	81
2012	23	20	43
Total			167
Independent support academic units			4
Grand total			171

Table 1.5. *External evaluations of Greek HEIs by year*

The status of Greek higher education, according to the Bologna process stocktaking, is presented in Table 1.6.

Degree system		Degree
1	Stage of implementation of the first and second cycle	5
2	Access to the next cycle	5
3	Implementation of national qualifications framework	1
National implementation of ESG		
4	Stage of development of external quality assurance system	4
5	Level of student participation in quality assurance	4
6	Level of international participation in quality assurance	5
Recognition		
7	Stage of implementation of diploma supplement	5
8	National implementation of the principles of the Lisbon Recognition Convention	1
9	Stage of implementation of ECTS	5
10	Recognition of prior learning	2

Table 1.6. *Bologna process stocktaking [BOL 09]*

The difficulty in the application of a quality assurance policy in Greek HEIs is, by analysis of Greek policy documents, well established as indicated in [KAV 11]. It is important to note the existence of difficulties in the implementation of quality assurance procedures after the voting of a law. ADIP (Hellenic Quality Assurance Agency for Higher Education) reported that it has encountered a number of difficulties and bureaucratic problems in its operation. As ADIP stated in four different reports, these problems often did not emanate from actors, who were against the philosophy, structures and implementation of the law, but from the political leadership and the government itself; see for example [ADI 09, ADI 12].

The latest reform of Greek higher education was imposed by Law 4009/2011. The new Framework Act for higher education entitled “Structure, operation, quality assurance and internationalization of HEIs” was the first, in the history of modern Greece, to gain support from both major political parties (the socialists and the conservatives). For the first time, three-quarters of the Greek Parliament voted in favor of the Framework Act for higher education.

One of the major reforms was the change in the electoral system of rectors. Under the new system, rectors are appointed by a governing board following an internationally published call for applications. The aim is to tackle a long-lasting problem in Greek higher education, which is the active involvement of political parties, through their youth, in the election of the rector. Another notable reform was the abolition of the academic asylum law. The so-called university asylum, or academic asylum as stated in the law, had been a result of the student uprising in 1973. The initial purpose of this was to reassure the free movement of academic ideas within a safe university environment. However, for many years, this part of the law had been violated by extremists who used university grounds to avoid arrest, before, after or during violent demonstrations [PAP 11].

Contrary to expectations, the introduction of this reform has been received positively by the general public and most importantly by the majority of the students, as is revealed by an overview of Greek media of the period. On the other hand, there was a strong opposition from a number of university rectors and a left-oriented minority of academic staff and students. For the time being, part of the law concerning the rectors' election has not been implemented. At this moment (05/2012), taking into account the Greek debt crisis, the strong public opposition to the austerity measures by the IMF and the Troika and the somewhat unstable political situation, the implementation of the latest Framework Act remains uncertain.

1.5.3. Accreditation of higher engineering education in Greece

A brief description on an accreditation scheme for Greek higher engineering education is presented in [TRE 07]. In Greece, the engineering academic title “Graduated Engineer” followed by the respective specialization, e.g. *Civil Grad. Eng.*, is protected by the Law 1477/1938; therefore only an engineering department belonging to one of the technical universities or faculties of engineering in universities is allowed to award this title.

The equivalence of foreign academic titles, along with the previous title of Graduate Engineer is granted by the DOATAP (previously DIKATSA) (Inter-university Center for the Recognition of Foreign Titles of Studies) being the competent authority for the recognition of diplomas of foreign universities. As all Greek engineering faculties offer curricula of five years for the first degree (diploma), equivalence is recognized only for those diplomas from abroad that have a similar total duration of studies. For degrees of duration less than five years, the candidate has to

follow and pass exams in additional courses so that equivalence can be granted.

The accreditation and admission to the profession of engineer in Greece is the responsibility of the Technical Chamber of Greece (TEE), established to “advance the education and training of engineers and to promote the science of and practice of engineering for the public benefit”. TEE has the right and the duty to evaluate the adequacy of the graduate’s preparation to start on a professional career. To this effect, it awards the “Permission of Exercising the Profession of Engineer” under the fulfillment of two prerequisites:

- A “Graduated Engineer” diploma, obtained (as previously explained) after a five-year engineering curriculum or an equivalent foreign title.
- An examination organized and run by the TEE. After successfully passing this exam, the applicant is enrolled in the TEE.

Once the “Permission of Exercising the Profession of Engineer” is granted to a graduate engineer, this remains valid for his whole professional life. It is to be noted that to date no similar examination procedure and acceptance exists for graduates from the short-cycle (three years) engineering curricula provided by the TEIs, a fact that leads to a lack of established “professional rights” for these graduates.

1.5.4. Selected cases on QA applications in Greek (engineering) HEIs

In the early 1990s, an attempt was made to introduce institutional or departmental evaluation (Article 24, Law 2083/1992) but met strong reactions from the opposition political parties and universities as well [ASD 09]. As indicated in [BIL 04], “in Greece, assessment or evaluation

could not be discussed by the university community until the early 1990s, since all initiatives in the past were taken by the Ministry of Education. Evaluation thus became another field for the traditional opposition between universities and state in Greece”.

Despite the strong resistance against any national evaluation framework, Greek HEIs have participated in various international evaluation projects since the mid-1990s. This “initial” movement toward a quality culture is attributed mainly to two interrelated reasons: the first reason is the sensitization of some Greek HEIs (faculty staff and leadership) to the whole concept of quality and evaluation; this has resulted in a number of initiatives that were taken by the HEIs themselves. The second was the change in the policy applied by the State, i.e. a transition from a top-down process (where the MoE centrally plans and controls the evaluation procedures) to a bottom-up process where the institutions are taking initiatives.

In the European pilot program “European Pilot Project for Evaluating Quality in Higher Education” implemented in 1994–1995, two Greek HEIs, namely the Department of Electronic Engineering and Computer Engineering of National Technical University of Athens (NTUA) and the Department of Electrical Engineering of TEI of Patras, participated [MOE 96].

Greek HEI participation in international quality assurance initiatives, as well as, similar national attempts as part of the Europeanization process is presented in [BIL 04, ASD 09, KAV 11]; therefore, they are not discussed here.

The evaluation of a Greek engineering department (Department of Production Engineering and Management of the Technical University of Crete) is reported in [POL 04]. The method used was a value-focused approach within the

framework of multi-criteria analysis methodology. According to this methodology, the department's global performance depends on a set of criteria representing service characteristic dimensions. The department's performance on these discrete criteria is able to prescribe its global performance. For the identification of the effect that the different dimensions and functions of the department exerted on its global performance, performance/importance diagrams were constructed.

The process used for the evaluation of the department consisted of four phases: (1) preliminary analysis, (2) self-evaluation, (3) review visit and (4) results.

The evaluation model consisted of five basic dimensions: (1) administration, (2) education, (3) research, (4) graduate satisfaction and (5) acceptance from the labor market.

The external reviewers, along with representatives of the department (professors, staff office, students), specified the weights of the five basic dimensions according to the objectives and scope of the department. The resultant excellence model of the department closely resembles the EFQM model. The evaluation process of the department was initiated on March 1999 and ended in December of the same year.

Some years later (2005), the Department of Electronics/School of Technological Applications/TEI of Thessalonica decided to use a modified EFQM model for self-assessment and (in accordance with Law 3374/05) for satisfying the requirements implied by possible collaborations within the EHEA. A task-force group was formed and the self-assessment process was realized during the academic year 2006–2007. The outputs were as follows:

- A definition of strengths and areas for improvement against each sub-criterion of the model, i.e. a type of SWOT analysis.
- A set of prioritized actions that can be integrated into the business planning process.
- A score for each sub-criterion and criterion.
- An overall score.

The modified EFQM model, as well as the implementation process, were presented in [SPA 08] and therefore not considered here.

The extent of use of the ISO standards in Greek universities till 2006 was reported in [PAP 10]. Data revealed that ISO standards were applied in 6 Greek universities out of the total 21. When a university was implementing ISO standards it was usually in separate laboratories or academic support services but not in the entire university. Authors found 23 cases in which ISO 9001:2000 were applied and 11 cases for EN 45001/ISO 17025 application. Out of the wide variety of laboratories implementing ISO standards, ISO 9001:2000 and ISO 17025 were the most “popular” in engineering (mechanical, chemical and civil) laboratories and in the medical field laboratories. On the other hand, academic support services such as research committees and libraries had also implemented ISO 9001. Authors also pointed out the difficulties in obtaining reliable information regarding the number of ISO 9000 registered educational institutions.

To the author’s knowledge, there is no updated data available concerning the diffusion of ISO standards to Greek HEIs. On the other hand, the Hellenic Open University, from 10/2008, is the only Greek HEI certified according to ISO 9001:2008 for its entire operations (provision of distance education in both undergraduate and postgraduate levels,

development and utilization of appropriate learning material and methods of teaching, planning and implementation of research projects, etc.).

The procedures followed for the application of quality principles and practices to an engineering department (Department of Mechanical Engineering/University of Thessaly) in the period 2002–2008 are presented in [STA 10]. It should be noted that the time period referred to is the transition period for HEIs, from voluntary participation to European quality initiatives to the implementation of the national quality assurance framework (Law 3374/2005); see also section 1.5.2.

In the case of this department, a mission statement was finally agreed upon, in 2008 focusing on the following objectives:

- To produce new fundamental and applied knowledge and know-how, through systematic research.
- To promote critical thinking aimed at enhancing the knowledge, skills and capabilities of its students and researchers through inspired teaching.
- To provide high-level services and consulting at a local, national and international level.
- To succeed in the competitive contest for research funding and human resources.
- To ensure the quality of all types of service that it provides and to reward its staff for its efforts in the best possible way.

The curricula reform was designed along the following lines, which reflect a strategy toward the development of a quality culture:

- 1) Reinforcement of the laboratory skills of the students and integration of case studies in all courses.

2) Training in the use of modern computational tools, introduction of new subjects and teaching modes.

3) Development of an inclusive diploma study plan (course credits – weekly student load – interdependence of courses – integration in course cycles).

4) Support for all courses via the development of functional web pages, including course material, a variety of references, books, foreign language bibliography, software, technical rules, professional regulations and directives.

5) Establishment of a quality assurance office, to coordinate and support the continuing development of teaching, research and service quality standards, indices and self-evaluation processes and also to develop and maintain a network for regular contacts and feedback reception by the alumni.

An overview of the QA system applied at the Technological Education Institute of Larissa is presented in [TRI 12]; see also [TRI 09]. The road to application of Law 3374/2005 is described through the investigation of leadership, culture, student satisfaction, graduate assessment and teaching performance evaluations. Two frameworks of service quality measurement based on SERVQUAL were summarized referring to the quality of teaching and administration: First, Owlia and Aspinwall's theoretical framework of service quality [OWL 96] with an emphasis on teaching aspects of education (academic resources, competence, attitude, content, etc.) and second, Waugh's [WAU 01] model of administrative and supportive services quality (tangibles, reliability and responsiveness, assurance and empathy). Quality assessment by students and graduates was performed by properly designed questionnaires. A previous study on service quality assessment at the Technological Education Institute of Serres was based on similar methodologies, i.e. the standardized SERVQUAL instrument [PAR 97] was used,

in which only the language adjustment was made, to fit in the academic environment; see [ZAF 08]. The findings revealed an existing gap in the way students and staff regarded education quality. This gap consisted mainly of differentiations concerning expected and perceived quality. Staff had greater expectations, but they perceived current educational services, on the other hand, to be of a higher level. Students had lower expectations and they perceived current educational status to be of a lower level [ZAF 08].

As has already been mentioned in section 1.5.2, one of the four axes of “evaluation criteria and indices” of the Law 3374/2005 is the “quality of the research work” performed in the HEI. In general, for the assessment of this aspect, a variety of approaches have been proposed, including expert-based qualitative approaches, such as evaluation by widely accepted researchers in specific disciplines with broad recognition in the scientific community (peer-review methodology). However, the rapid Internet proliferation and the easier access to scientific databases offer an alternative approach to assessing the scientific outcome of a researcher or a faculty. Nowadays, there seems to be a movement toward bibliometric measures and indices [ALT 12].

To the author’s knowledge, there are only a few published studies by bibliometric methods concerning evaluation of HEIs or their departments in Greece and in south-eastern Europe. A piece of research in 2010 was focused exclusively on Greek Computer Science departments examining 552 faculty members using the Google Scholar and Publish or Perish software [LAZ 10]. In a similar previous publication, in 2008, an evaluation of Chemistry, Materials Science, Chemical Engineering and Physics in Greek university departments was presented. Six-hundred-and-one faculty members were assessed using the h-index as calculated from the Web of Science scientific database [KAT 08]. Recently, 93

Greek university departments from the fields of social sciences and humanities, sciences, engineering, pharmacy and economics were evaluated according to their faculty members' h-index using the Google Scholar scientific database [ALT 12], while the evaluation of the engineering departments of TEIs was done by a combination of a number of simple bibliometric indices and by using Scopus and was presented in [VAX 11].

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Chapter 2

Mechatronics Education

New technology and products necessitate the teaching of mechatronics either as a separate discipline or as part of mechanical engineering. However, there are a lot of differences in perceiving the meaning, scope and objective of mechatronics. In this chapter, the concept of mechatronics is explained with reference to its historical development and its application in developing mechatronic products. A review on mechatronics education is presented. A discussion about how mechatronics education can be imparted is provided. Sample course structure has also been included. Some examples of mechatronics projects are presented. The chapter concludes with a discussion about challenges in mechatronics education and possible measures to overcome these challenges.

2.1. Introduction

Although engineering is as old as civilization, formal education in engineering started to gain popularity from the beginning of the 19th Century. In the beginning, engineering

Chapter written by Uday Shanker DIXIT.

consisted of two distinct disciplines – military engineering and civil engineering. Military engineering was concerned with the design, development, manufacture and maintenance of war-related infrastructure. Civil engineering was concerned with the engineering of all non-military applications. The spread of the Industrial Revolution and developments in the transportation sector provided impetus to the emergence of a new discipline of mechanical engineering. Research in the development of the electrical motor gained momentum from the beginning of 19th Century, but practical application only started in the last quarter of the century. The discipline of electrical engineering developed to cater to the specific need of power generation and motors. Later on, disciplines like electronics, instrumentation and computer science emerged from electrical engineering. Similarly, production engineering, industrial engineering, chemical engineering, metallurgical engineering and so on inherit a number of features from mechanical engineering. As engineering is an applied science and art, the employability of graduates affects the creation of the discipline to a great extent. Thus, market needs put the pressure on academics to modify the existing engineering program or create a new one. This is true in the case of mechatronics, which emerged as a discipline due to requirement of engineers for designing, operating, manufacturing and maintaining a number of products needing a synergistic involvement of more than one discipline for their development. Some examples of such products are robots, computer numerical control (CNC) machine tools, photocopiers and modern aircrafts.

The term mechatronics was first coined by a Japanese engineer named Tetsuro Mori of the Yaskawa Electric Corporation. The trademark rights for the term “Mechatronics” were granted to Yaskawa in 1971. Yaskawa elected to abandon its rights on the word in 1982. Now mechatronics is understood as the synergistic combination of mechanical engineering, electrical engineering, electronics, control engineering,

system design engineering and computer engineering to create and maintain useful products.

Mechatronics entered the academic sector in two distinct forms – as a course and as an engineering discipline. This chapter discusses various aspects of mechatronics education including the difficulties and challenges.

2.2. A brief history of mechatronics

The word mechatronics is a combination of the words – mechanical and electronics, and these two disciplines have major influences on the development of mechatronics. It will be appropriate to discuss a brief history of mechanical and electronics engineering before understanding the growth of mechatronics. Accordingly, this chapter is divided into three subsections covering the history of mechanical engineering, electronics and mechatronics. The information presented in this section is scattered over several places, but a good reference is [GAR 98].

2.2.1. History of mechanical engineering

The history of mechanical engineering is very old. In the Hellenistic period (323–146 BC), Greek civilization was at its zenith. The Greek mechanical engineer or *mechanomai* used to apply the principles of science and art in various mechanical gadgets. Archimedes (287–212 BC) was a leading scientist and engineer from that period. He explained the principle of lever and designed a number of innovative machines including the screw pump. The screw pump called Archimedean screw was used to pump water.

Machinery in antiquity was either powered by man or water. Water mills were used to grind corn and drive powerful forging hammers and bellows for metallurgy. In some places, mining hoists were driven by water wheels. The

cogwheel and gear wheels evolved with water wheel technology. A 5th Century BC poem mentions a water wheel. Heron of Alexandria (AD 10–70) describes a wind organ with a piston providing air for the organ pipes. The organ piston is moved by rotating a wheel. Thus, the slider crank mechanism was known at that time. Heron described the construction of *aeolipile*, a rocket-like reaction engine and the first recorded steam engine. The first vending machine was also his construction. When a coin was inserted into a slot on the top of machine, a fixed amount of holy water was dispensed. Heron authored a book on mechanics and optics.

Philon of Byzantium (280–220 BC) discusses catapult design in his book *Compendium of Mechanics*. Termed as either a dart thrower or stone throwers, they evolved as a class of machines from the 4th Century BC to remain as a mainstay of armies, until the invention of gun powder. Philon has also described pneumatic machines.

Ships are an example of wood and water technology. Oared ships were favored as warships by the Egyptians during the reign of Ramses III (1198–1166 BC). Archimedes designed a huge galley named the *Syrakosia*. The vessel was the first three-mast ship in the world.

In the medieval period, scholasticism (1100–1500 AD) aimed at the reconciliation of faith and reason. It unwittingly promoted the development of mathematics and science. During the medieval period, a lot of developments were made in civil engineering, metallurgy and basic sciences. Indian smiths had developed the wootz process for developing steel. This technology first appeared in the first millennium AD. We do not see much development in mechanical engineering during this period. Most of the machines were driven by animal power or water. Windmills were also prevalent during this period.

The development of science and technology suffered as a result of the Hundred Years War (1337–1453) in France and the bubonic plague. This pandemic is known in history as *Black Death*, which was at its peak in Europe, from 1348 to 1350. It killed one-third of the population of Western Europe, particularly in England, France, Spain and Germany. The rebirth of science and technology took place during the Renaissance, a cultural movement that spanned roughly from the 14th to the 17th Century. In the early period of the Renaissance, science and art were intermingled, the example being the works of Leonardo da Vinci. Leonardo da Vinci systematically studied aerodynamics. He is called the “father of modern science” by some historians.

Among the physical and mechanical problems examined by Renaissance scientists, two were of fundamental importance to mechanical engineering: (1) the composition of forces and the law of force parallelogram and (2) the problem of bending of a beam. Galileo Galilei (1564–1642) was an Italian physicist who contributed a lot to the science of mechanical engineering. Galileo has designed and fabricated a number of instruments, for example the thermometer that utilized the principle of the expansion of air. He also designed an escapement mechanism for a pendulum clock. This mechanism converts the rotational motion of a gear into an oscillating motion. Sir Isaac Newton (1642–1727) published *Philosophiae Naturalis Principia Mathematica* in 1687. In his book, Newton described universal gravitation and the three laws of motion.

The ancient philosophers and men of science in Persia and Greece proposed four basic elements of the universe, i.e. earth, air, fire and water. In the Indian tradition, in addition to these, space is also considered a basic element. Of these, air and water were used as prime movers. However, it was only in the 17th and 18th Centuries that the use of heat as a

source of power was explored. On 2 July 1698, Thomas Savery (1650–1715), a military engineer, patented an early steam engine for the raising of water. He demonstrated it to the Royal Society on 14 June 1699. He first used the term “horsepower”. Thomas Newcomen (1664–1729) developed a steam engine around 1710. James Watt modified Newcomen’s engine. Watt’s engine used 75% less coal than Newcomen’s. Newcomen’s and Watt’s early engines were powered by the vacuum generated by condensing steam instead of the pressure of the expanding steam. Watt invented the steam condenser, parallel motion gearing, double action engines and the centrifugal governor.

Originally, engineering had only a military meaning. In 18th-Century Europe, the meaning was expanded and given a civil application like in the building of canals and bridges. John Smeaton (1724–1792) is often regarded as the father of civil engineering. He also employed his skills in mechanical engineering. He developed the water engine and water mill. He also improved Newcomen’s steam engine. With the advent of steam, mechanical engineering started flourishing.

Nicolas Leonard Sadi Carnot (1796–1832), the French military engineer, is called the “father of thermodynamics”. At the age of 28, he published his seminal work *Reflexions sur la Puissance Motrice de Fe* (*Reflections on the Motive Power of Heat*). He suggested one ideal thermodynamic cycle called the Carnot cycle. An engine operating between two temperatures will have the highest thermal efficiency, if it works on the Carnot cycle. Even though Carnot died of cholera at the age of 36 in 1832, because of his contribution, he is often considered the “father of thermodynamics”.

The German theoretical physicist, Rudolf Julius Emmanuel Clausius (1822–1888), and the French civil engineer, Benoit Pierre Emile Clapreyron (1799–1864), jointly provided the Clausius–Clapreyron equation. Around the same time James Prescott Joule (1818–1889) discovered

the equivalence of heat and mechanical work. The work of these three scientists resulted in the formulation of the first and second law of thermodynamics.

Nikolaus August Otto (1832–1891) produced a small four-stroke internal combustion (IC) engine in 1861. Alphonse Beau de Rochas took out a patent in 1862, describing only the main details of a four-stroke cycle. He did not provide any suggestions on how it might be used. Therefore, it is believed that Otto independently invented the same cycle.

Jean Étienne Lenoir (1822–1900) took out a patent on IC engines two years before Beau de Rochas in 1860. He used illuminating gas for his engine and by 1865 produced over 300 engines ranging from 1/3 to 3 horsepower. These engines were four-cycle, low in compression and inefficient. Illuminating gas, also known as town gas, contains hydrogen, methane and carbon monoxide. Lenoir put one engine on a carriage and created a motor car. Later he installed one engine in a boat.

Otto also described a working two-cycle engine, but this was invented by Sir Dugald Clerk, born in Glasgow, Scotland in 1854. The early engines had the rotational speed of about 200 rpm. Gottlieb Daimler (1834–1899) developed engines working at about 1,000 rpm. In 1892, Rudolf Diesel (1858–1913) developed a diesel engine using compression ignition.

The first steam-powered automobile was developed in 1769. An IC engine working on a gas mixture was developed in 1806 for use in automobiles. In 1826, Samuel Brown tested his hydrogen-fueled IC engine by building it to propel a vehicle. In 1870, an Austrian inventor S. Marcus placed a liquid-fueled IC engine on a simple handcart, which was the first vehicle run by gasoline. Practical automobiles running on petrol or gasoline were developed around 1885. In 1838, Robert Davidson had built an electric locomotive that attained a speed of 6 km/h.

These technological developments helped the industrial revolution during the rapid industrial development in the late 18th and early 19th Centuries. It started with the mechanization of the textile industries, the development of iron-making techniques and increased use of refined coal. The development of machine tools in the first two decades of 19th Century helped to produce more machines. The second industrial revolution started in 1850 with the development of steam-powered ships and railways. The developments of IC engines and electric power generation boosted the industrial development. John Stevens (1749–1838), called the “father of American railroads”, developed the first machine shop delivering mass production in 1804.

Early mechanical engineers used the principles of physics to invent, design and develop the machines. Frederick Winslow Taylor (1856–1915) introduced management into mechanical engineering. He was a mechanical engineer and was interested in improving the efficiency of production. He is called the “father of scientific management”. He also researched into machining. He developed an empirical relation between cutting speed and tool life. F.W. Taylor is often known as the father of industrial engineering. In the United States, Henry R. Tone was a pioneer in developing the industrial engineering field. He was a member of ASME. In 1948, a new society, the American Institute for Industrial Engineers, was founded. Table 2.1 shows some landmark events in the history of mechanical engineering.

2.2.2. History of electronics engineering

Electronics was born from electrical engineering, which in turn accelerated the development of computer hardware. The history of electronics will include a portion on the histories of electrical engineering and computer science. The history of electrical engineering can be considered from the beginning of 19th Century. The concept of the direct current (DC) was

discovered by Michael Faraday (1791–1867) who deduced the principle of the generator and transformer. William Sturgeon (1783–1850), an English physicist, invented the first practical electric motor. Thomas Davenport (1802–1851), an American blacksmith, patented an electric motor in 1837, which was used to power machine tools and printing presses. Due to the high cost of primary battery power, the motors were commercially unsuccessful and Davenport became bankrupt. In those days, electricity distribution was unavailable. The modern day motor was invented accidentally by Zenobe Gramme, when he found that the dynamo invented by him was reversible. In 1888, Nicola Tesla invented the first AC motor. The application of electric motors revolutionized industry, as the power transmission losses were minimized.

Although the history of electronics starts with the development of the vacuum tube in 1883, it grew rapidly after the invention of the transistor by John Bardeen, Walter Brattain and William Shockley in 1947. In acknowledgment of this accomplishment, Shockley, Bardeen and Brattain were jointly awarded the 1956 Nobel Prize in Physics for their research on semiconductors and the discovery of the transistor effect. The concept of the integrated circuit was proposed by Geoffrey W.A. Dummer in 1952. In 1958, Texas introduced the first commercial integrated circuit. The first handheld calculator was developed in 1967. In 1968, Burroughs produced the first computer to use an integrated circuit.

Starting from the early part of the 1970s, a number of mechanical products started using microprocessors. In 1971, Intel® produced the first commercial microprocessor 4004. It uses 2,300 transistors and has a clock speed of 108 kHz. In 1980, Intel® introduced the first 32-bit microprocessor. In 1981, IBM introduced a personal computer with an industry standard disk operating system (DOS). In 1990, the World

Wide Web (WWW) was set up by Tim Berners-Lee at the European Particle Physics Laboratory in Switzerland. In 1993, Intel® introduced the Pentium® processor. In 2000, Intel® introduced Pentium® 4, which uses about 42 million transistors and has a clock speed of 1.4 GHz. In 2006, Intel® introduced the Core 2 processor.

Event	Year
The first steam engine (used as a water pump) by Thomas Savery	1698
Steam engine installed by Thomas Newcomen	1712
The first tandem rolling mill patented by Richard Ford	1766
The first commercial steam engine based on James Watt's design	1769
Richard Trevithick developed a high-pressure engine	1799
The first car powered by an IC engine running on fuel gas	1806
George Stephenson (1781–1848), the father of railways, designed his first locomotive	1814
Samuel Brown patented first the IC engine to be applied industrially	1823
Nikolaus Otto developed a practical four-stroke cycle IC engine	1876
Karl Benz got a patent for a two-stroke IC engine	1879
James Atkinson developed the Atkinson cycle engine	1882
Herman Hollerith invented an electro-mechanical machine to tabulate information using cards with punched holes	1890
Rudolf Diesel demonstrated the diesel engine using a peanut oil fuel (bio-diesel)	1900
The first working gas turbine by Aegidus Elling (1861–1949), the father of the gas turbine	1903
Wright brothers applied for patents for their flying machine in Germany and France	1904
The first successful military plane	1909
Boeing's first passenger aircraft	1928
The first NC machine at MIT	1952
The first CNC machine at MIT	1957

Table 2.1. *Some landmark events of mechanical engineering*

2.2.3. Growth of mechatronics

The term mechatronics was coined in 1969, but the advent of mechatronics can be traced back to the early 1950s. A prototype numerical control machine tool was demonstrated at the Massachusetts Institute of Technology (MIT) in the United States. It was a retrofitted milling machine. In 1957, the first CNC machine was developed at MIT. In 1961, the part programming language Automatically Programmed Tooling (APT) was released for automatic machining of the components on CNC machines. The operation and maintenance of CNC machines required an engineer to be skilled in mechanical engineering, electronics and programming. Thus, the need for a new discipline was felt.

Development of robotics is also linked with the growth of mechatronics. In 1959, the Planet Corporation introduced the first commercial robot based on limit switches and cams. In 1961, a Unimate robot was installed by Ford to service a die-casting machine. In 1978, a Programmable Universal Machine for Assembly (PUMA) robot was introduced by Unimation. The PUMA robot had six degrees of freedom with revolute joints that were operated by DC servo motors. In 1979, the Selective Compliance Arm for Robotic Assembly (SCARA) was developed by Yamanshi University in Japan. A SCARA robot has all its axes for revolute joints along a vertical direction. This makes the SCARA robot rigid along z -direction and compliant along x - y -direction. That is why it is called a selective compliance arm. In 1998, Honda introduced the P3 humanoid robot. In 1999, Sony introduced the AIBO robot dog. AIBO is acronym for Artificial Intelligence Robot. In 2000, Honda introduced ASIMO a humanoid robot. ASIMO is an acronym for Advanced Step in Innovative MObility. In 2007, TOMY, USA, introduced the i-SOBOT humanoid robot. The robot i-SOBOT is endowed with 17 custom developed servo motors, 19 integrated circuit

chips, a built-in gyrosensor, two light emitting diodes, voice command recognition and can speak and perform hundreds of words, phrases and preprogrammed actions, over 90 kinds of sound effects and can play five songs.

In 1971 and 1978, the Japanese Ministry of International Trade and Industry (MITI) passed legislation that encouraged joint research between the machinery and electronics industries. By 1990, mechatronics had established itself as an important field of engineering and the *Mechatronics* journal was launched in the United Kingdom by Pergamon Press. This journal covers technical innovations in the field of mechatronics. In 1996, IEEE–ASME launched the *Transactions on Mechatronics* journal.

Mechatronics is evolving as the technological developments are taking place in various areas. Tomozuka (2002) has pictorially depicted the evolution of mechatronics from 1970 to 2000 in Figure 2.1, which shows that electronics and control theory were major players in mechatronics at the beginning. At present embedded systems, information technology (IT) and decision making has an important role.

2.3. Definitions and scope of mechatronics

Mechatronics has been defined in a number of ways. Various definitions can be found in research papers, books, university brochures and industry catalogs. It is difficult to trace the original author of the definitions and this will not be attempted here. The main aim of this section is to critically analyze the definitions to understand mechatronics more clearly. Some definitions are as follows:

DEFINITION 2.1.— *Mechatronics systems are the systems dealing with the movement of mass, electrons and information.*

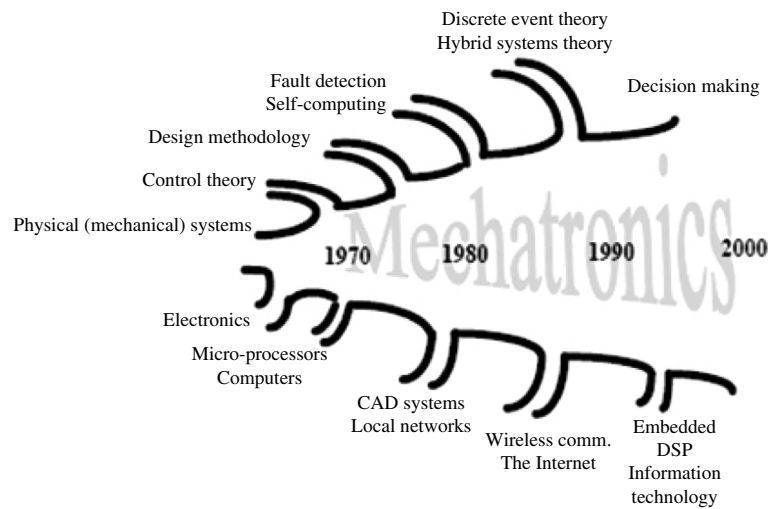


Figure 2.1. *Evolution of mechatronics. With permission from [TOM 02]© 2002 Elsevier*

This definition on the one hand is too general and on the other hand excludes many products, where there is no movement of mass. For example, an electric rice cooker can be considered a consumer mechatronic product, although there is no movement of mass in it. Moreover, this definition does not explicitly talk about the integration of different disciplines.

DEFINITION 2.2.— *Mechatronics is the ability to integrate electronics and computing technologies into a wide range of primarily mechanical products and processes.*

This definition talks about the integration of different disciplines. However, it restricts the scope of mechatronics by restricting it to mechanical products and processes. With this definition a CD-writer may not be called a Mechatronic product. Although this product is a part of computer

hardware, it involves integration of mechanical engineering, electrical devices and electronics.

DEFINITION 2.3.— *Mechatronics is the synergistic integration of mechanical engineering with electronics and intelligent computer control in the design of products and processes.*

In this definition, an important term is “synergistic”; the dictionary meaning of which is “of and relating to synergy”. One meaning of “synergy” is “the interaction of two or more agents or forces so that their combined effect is greater than the sum of their individual effects”. Thus, the definition brings out the power of mechatronics, which is much more than the sum of the powers of different disciplines. However, the definition restricts mechatronics to the domain of design. Actually, mechatronics find applications in manufacturing and maintenance as well.

DEFINITION 2.4.— *Mechatronics is the application of methodology, techniques and understanding of one or more disciplines to another discipline.*

This definition is sufficiently general to encompass all types of present and future products. It is possible that future products may have enough portions of biotechnology or other related areas. Thus, there have to be engineers who can understand different disciplines. However, this definition misses the important aspect of “synergy”.

DEFINITION 2.5.— *Mechatronics is the synergistic combination of precision engineering, electronic control technology and systems thinking in the design of product and processes.*

This definition was provided by the European Union-sponsored Industrial Research and Development Advisory Committee working group in the late 1980s. This definition restricts mechatronics to the domain of design.

DEFINITION 2.6.— *Mechatronics is the application of complex decision making to the operation of physical systems.*

This definition overemphasizes the decision-making process. There can be mechatronic products involving the integration of different disciplines without having a decision-making capability in the product.

DEFINITION 2.7.— *Mechatronics is the synergetic integration of physical systems with information technology (IT) and complex-decision making in the design, manufacture and operation of industrial products and processes.*

This definition rightly expands the scope of mechatronics to design, manufacture and operation. It also includes the important word “synergetic”. The definition stresses IT and complex decision making, but misses the mention of mechanics and electronics.

Based on these definitions and considering the present day scope of mechatronics, the following definition is proposed:

Mechatronics is the synergetic integration of mechanical engineering, with electrical engineering and/or electronics, and possibly, with other disciplines, for the purposes of design, manufacture, operation and maintenance of a product.

This definition channels the scope of mechatronics to products having sufficient content of mechanical and electrical or electronics discipline. At the same time, it accepts the scope of other disciplines. Moreover, it brings out the applicability of mechatronics for design, manufacture, operations and maintenance.

2.4. Examples of mechatronic products

We can provide a number of examples of mechatronic products. Computer numerically controlled (CNC) machines, robots, material handling systems and flexible manufacturing systems (FMS) are a few examples of mechatronic products in manufacturing. In automobiles, the antilock mechanism of four-wheelers, the electronic ignition system, the engine control system and so on are all examples. In consumer products, cameras, washing machines, toasters, photocopiers are mechatronic products. In civil engineering, smart structures fall into the category of mechatronic products. Figure 2.2 shows some mechatronic products used in industry.

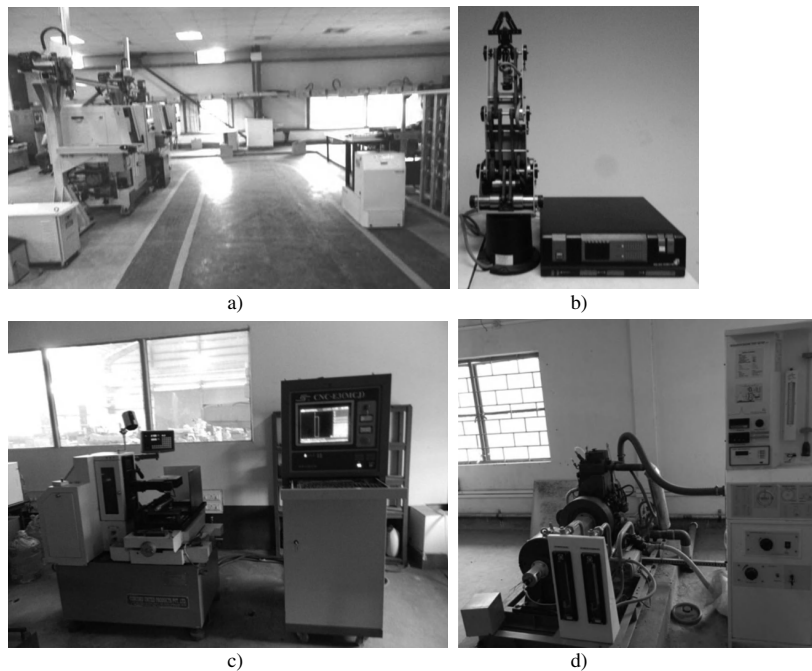


Figure 2.2. Some examples of mechatronic products: a) a flexible manufacturing system, b) a robot, c) a wire-cut electro-discharge machine and d) an engine testing rig

There are generally two types of mechatronic products. In one type of product, electronics, electrical equipment or computers have enhanced the capabilities of a mechatronic product, but the basic structure remains the same. Examples are CNC machines. In other type of product, electronics have totally replaced mechanical functions. An example, is the electronic watch.

Several examples can be cited, where mechatronics have been applied to enhance the quality of the product. CNC machines can produce accurate and complex shapes compared to their traditional counter parts. IC engines can be equipped with electronic control. Many consumer products such as washing machines, refrigerators and air-conditioning systems have been made more efficient and attractive by integrating electronics within them. These products can be called mechatronic products.

There are several products that have been totally replaced by electronics. For example, a digital electronic watch does not have moving parts like its mechanical counterparts. Similarly, with the development of electronics, the speed of motors can be controlled efficiently, removing the use of belt, chain and gear drives. Electronic cams can be used in place of traditional cams. In electronic cams, the follower is a nut, which can be moved up and down by a ball screw. The rotation of a ball screw can be controlled by a stepper motor.

It is worth mentioning that of late there has been a trend of replacing all mechanical elements with electronics. This tendency should be avoided. Instead the best solution must be searched. For example, sometimes putting a mechanical indicator may be more cost-effective and reliable than an electronic indicator.

2.5. Review of literature in the area of mechatronics education

Education in mechatronics has started gaining popularity starting from early 1990s. A number of papers have been published in the area of mechatronics education. Some papers are briefly summarized.

Fraser *et al.* [FRA 93] have described how mechatronics can be taught within the traditional curriculum by illustrating the mechatronics teaching practice at Dundee Institute of Technology in the United Kingdom. The authors have suggested including the following topics in the mechanical engineering curriculum: (1) systems design, (2) microprocessor technology, (3) digital electronics, (4) digital and analog interfacing techniques, (5) digital communications, (6) software development, (7) sequential control of electrical, pneumatic and hydraulic systems and (8) control principles. The authors have described two examples of mechatronic products:

- 1) Design of a diameter measurement device for a harvesting head: a harvesting head is a mechanical or hydraulic attachment to a vehicle that fells and prepares trees to a condition suitable for carrying to sawmills. The objective of the project was to design a system for measuring the diameter of trees. The designed system is shown in Figure 2.3.

- 2) Automation of the handle attachment process for woven polymer sacks: a local company was facing a problem in attaching handles to the woven polymer sacks due to worker absenteeism. It was decided to automate the system. A pneumatically operated system controlled by a programmable logic controller (PLC) was designed. It was tested on shop floor conditions.

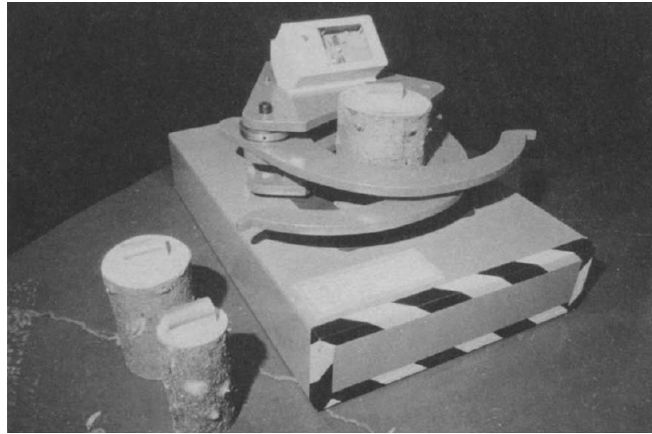


Figure 2.3. *Diameter measuring device for a harvesting head.*
 With permission from [FRA 93]© 1993 Elsevier

Hanson [HAN 94] discussed the teaching of mechatronics at the master's level, with reference to teaching at the Royal Institute of Technology, KTH in Sweden. The author has concluded that a project-oriented approach is beneficial in the teaching of mechatronics. He has discussed the application of mechatronics to the area of biomechanics. In the introduction, the author has provided an interesting history of mechatronics education at KTH. In the middle of the 1970s, digital electronics, microcomputer architecture, assembler programming and input or output interfacing were introduced in the curricula of mechanical engineering. Mechatronics was understood as "microcomputers in mechanical systems". In the beginning of 1980s, the focus was on embedded real-time control systems, and the expression "computer controlled mechanics" was used for mechatronics. In the 1990s, mechatronics was defined as mechanical devices and systems programmed or programmable with perception, action and communication. Systems of all sizes starting from nanotechnology to gigantic heavy industrial systems were included.

Acar and Parkin [ACA 96] have reviewed various aspects of mechatronics education. According to authors, mechatronics is not a new branch of engineering, but a newly developed concept that underlines the necessity for integration and intensive interaction between different branches of engineering. “Mecha” in mechatronics should be understood as the widest aspect of the physical embodiments of mechanical engineering, including optical elements, while “tronic” should be understood to embrace all aspects of microelectronics and IT including control. Authors also emphasize that many courses in mechatronics are simply gluing mechanical and electronics topics and lack a coherent integrative theme. Generalist and specialist approaches of education are compared. The Japanese approach to product developmental strategies and mechatronics education and training is discussed. The authors argue that the success of Japanese industry in designing, developing and marketing mechatronic products and system may be attributed to the Japanese approach to product developmental strategies, their education and their training system. The authors have emphasized the need for the involvement of industries in education.

Tan *et al.* [TAN 98] have discussed various developments in mechatronics in Asia from three perspectives: education, research and application of technology. The education scenario in the following countries was discussed in detail: Japan, Korea, Singapore, China, Taiwan and Hong Kong. The developments in Thailand and Indonesia were also briefly discussed. Many Asian countries offer degree or diploma programs in mechatronics. In almost all countries under the survey, the government has been the main support. Collaborative research with industry has been actively developed. A lot of interest is also being shown in microelectronics.

Lyshevski [LYS 02] has reviewed mechatronics education. The author has discussed the curriculum, software and books in mechatronics. The author has emphasized the need to include projects into the mechatronics curriculum. According to him, the mechatronics curriculum can be viewed as the vehicle by which students are introduced to the subject matter, multidisciplinary areas and disciplines. The author classified the mechatronics system as conventional mechatronic systems, microelectromechanical–micromechatronic systems (MEMS) and nanoelectromechanical–nanomechatronic systems (NEMS). The author points out that the theory governing the behavior of conventional and MEMS mechatronic systems are the same, but NEMS are governed by different theories including quantum theory.

Tomizuka [TOM 02] has presented a Y2K status report for mechatronics. He defined mechatronics as the synergetic integration of physical systems with IT and complex decision-making in the design, manufacture and operation of industrial products and processes. IT in the context of mechatronics includes computers and digital signal processors and the Internet. The ASME has identified the following eight areas to impact on mechanical engineering in a major way:

- 1) Information technology
- 2) Miniaturization
- 3) Materials science
- 4) Bioengineering and medicines
- 5) Energy
- 6) Transportation
- 7) Environmental engineering
- 8) Manufacturing.

In the last five areas, the visible mechatronics activities have already taken place, whereas, the first three activities are the enabling technologies. Mechatronics can also be used to take care of elderly people, which can be called human friendly mechatronics. The author has also discussed the research opportunities in mechatronics. Three mechatronics projects are discussed. These are vehicle lateral controls for automated highway systems, hard disk drives and material handling mechanisms for printing engines. The author suggests that the faculty members specializing in design and control must act as leaders to bring mechatronics into the engineering curriculum.

Gardner [GAR 02] has described two projects that were given in a senior-level mechatronics elective course at Penn State University. While one project was successful, the other was a failure. The author has suggested the following measures to make a successful project:

- The project goal should be kept in mind. The project should be formulated so as to impart the maximum learning in the desired area.
- The instructor should preferably design and fabricate the project by himself before assigning it to students. In this way, the difficulty level of the project will be known.
- There should be a balance between the hardware and the software.
- The project should be open-ended enough to allow for innovation.

Grimheden and Hanson [GRI 05] have described the ongoing process of establishing mechatronics as an academic discipline with examples from Northern Europe. Vaughan *et al.* [VAU 08] have described a sophomore-level course titled “Creative decisions and design”. The course includes mechatronics and technical communication. The authors have emphasized the importance of team work. However,

they also observed that in team work, students may not develop the capabilities in all the relevant areas and may divide the work according to their comfort/ability in an area. To alleviate this problem, during the early part of the course, each student was assigned individual projects involving fabrication. In the later half, the students were given team projects.

Habib [HAB 08] has described mechatronics and the required curriculum for teaching it. The author has emphasized the need to impart team, as well as, individual skills. There should be a balance between practice and theory. The author also emphasized the importance of a concurrent approach.

Ersoy [ERS 09] has discussed the problems due to different backgrounds of teachers of mechatronics. A case study of an institute in Turkey has been taken. The author has provided some suggestions for teachers of mechatronics. Teachers should motivate the students, facilitate to realize their potential and reward them for their success.

Wang *et al.* [WAN 09] have described the laboratory education at the CDHAW center of Tongji University in China. CDHAW stands for Chinese–German School of Applied Sciences. To properly train the students in mechatronics, four types of laboratories were developed – preliminary training laboratories, foundation laboratories, specialized laboratories and advanced laboratories. In the preliminary training laboratories, exposure to metal working and electrical or electronics is provided before theory learning. In foundation laboratories, the students verify the fundamentals of mechanics, physics, material science, circuit theory and so on. In the specialized laboratories, building blocks of mechatronics like control, sensors, actuators, PLCs, microprocessors and so on are introduced. In the advanced laboratories, students are supposed to work on their own projects. The main laboratories of CDHAW were the

automatic control laboratory, the sensor laboratory, the PLC laboratory, the industrial communication laboratory and the modeling and simulation laboratory. The immediate plan was to develop an FMS laboratory.

Lee [LEE 10] has presented a survey of mechatronics education in 15 universities of South Korea. Some universities offer mechatronics course in the department of mechanical engineering, while at some places there is different division or department for mechatronics. A list of courses offered in the years 2002, 2006 and 2008 is provided in Table 2.2. The table provides some idea about the change in the trend in mechatronics education. Bradley [BRA 10] has discussed pertinent issues of mechatronics based on his personal experience of more than 20 years.

This brief review of the literature indicates the growing interest in mechatronics education. It also highlights some differences of perception in understanding mechatronics and its education. In the subsequent sections, the different types, methods and modes of mechatronics education will be discussed.

2.6. Common doubts regarding the discipline of mechatronics

The following question is often asked: Can mechatronics be called a separate discipline? This question has partly been answered in the beginning of the chapter. Mechatronics is different from either electronics or mechanics, in the same way that mechanical engineering is different from mechanics and thermodynamics. There can be experts who specialize in mechanics or thermodynamics, but a mechanical engineer is taught both the courses from an application point of view. Similarly, a mechatronics engineer will have the knowledge of electronics, mechanics and other disciplines

from an application point of view. Someone has rightly said, “mechatronics practitioners will prototype the whole design, then the specialists in the various fields will take over the detailed design”.

Academic year 2002	Academic year 2006	Academic year 2008
Industrial optics (2)	Opto-mechatronics (1)	Opto-mechatronics (1)
Manufacturing networks (1)	Computer network (3)	Computer network (2)
Medical engineering (1)	Bio-engineering (3)	Bio-engineering (2)
MEMS (1)	Micro/Mobile robots (2)	Micro/Mobile robots (2)
Virtual engineering (1)	Virtual engineering (2)	Virtual engineering (1)
Nonlinear control (1)	Assembly engineering (1)	Painting & polymers (1)
Multivariable control (1)	Web-based engineering (1)	Web-based engineering (1)
Intelligent system (2)	Discrete event system (1)	Discrete event system (1)
Computer graphics	Engineering documentation (3)	Injection molding (1)
Car electronics (1)	Car electronics (1)	Car electronics (2)
Energy engineering (1)	Embedded system (2)	Real-time control (1)
	Laser engineering (2)	Laser machining (1)
	Wind power systems (1)	Wind power systems (1)
	Computerized logistics (1)	Ship mechatronics (1)
		DSP application (2)
		Noise control (2)
		Ultrasonics (1)
		Display devices (2)
		Renewable energy (2)
		Semiconductor process (1)
		Rotor dynamics (1)
		Chassis design (1)
		Chassis control (1)
		RP practice (1)

Table 2.2. University specific subjects in South Korea (the number in the parenthesis is the number of universities offering the course).
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Many technical papers published in the *Mechatronics* journal emphasize the control aspect. This provides the impression that mechatronics mainly deals with products requiring controls. Control engineering finds a lot of application in mechatronics just as it finds application in the other areas. However, mechatronics deals with even those systems that do not need sophisticated control technologies. In fact, sometimes even in the products requiring control, the simplified techniques like fuzzy set theory and neural networks have been employed, which are quite different from conventional control methodologies.

Similarly, sometimes an impression is created that mechatronics is basically robotics. In fact, there have been books dealing with these two topics together (e.g. [STA 94]). While robotics is an example of mechatronic products, mechatronics is neither limited to robotics, nor does it have to cover all the in-depth aspects of robotics.

2.7. Characteristics of mechatronics education

Engineering education is generally based on single discipline activities founded on a bottom-up approach. The bottom-up approach builds on fundamental principles and concepts before integrating them in the form of a final product. The top-down approach first provides the overall idea of the final product, although not in very detailed form and then studies the subsystems of the system in detail. Mechatronics education has to follow a top-down approach, because it involves many disciplines and students have to get an idea as to how the various disciplines will be integrated. Integration of various disciplines is an integral part of mechatronics. Integration has to be carried out in a manner so that one and one become 11 instead of one.

Another feature of mechatronics education and practice is that they follow concurrent engineering (CE) practice. CE is

a systematic approach to integrate concurrent design of products and their related processes, including manufacture and support. This approach is intended to make the developers from the outset consider all elements of the product lifecycle from concept through to disposal, including quality, cost, schedule and user requirements. CE is a business strategy that replaces the traditional product development process with one in which tasks are done in parallel and there is an early consideration for every aspect of a product's development process. This strategy focuses on the optimization and distribution of a firm's resources in the design and development process to ensure effective and efficient product development process. Just meeting the specification is not enough in CE. The designer has to keep in consideration, mass production, cost and quality. CE has often been practiced under different names such as Simultaneous Engineering, Lifecycle Engineering, Parallel Engineering, Multidisciplinary Team Approach, Integrated Product and Process Development and so on. The major objective of CE is to overlap the different phases of design to reduce the time needed to develop a product. It requires the simultaneous, interactive and interdisciplinary involvement of design, manufacturing and field support engineers to assure design performance, product support responsiveness and lifecycle reliability. Each team member is involved in all the aspects from the beginning.

In conventional design methodology, mechanical design should be done first followed by electrical or electronics and software design. This is schematically shown in Figure 2.4. This approach is quite inflexible and often distant from an optimum design. In the optimum design of a mechatronics product, at every stage of design, each discipline has to be involved. The design involves five phases: deciding specifications, conceptual design, embodiment design, detailed design and prototyping. Figure 2.5 shows a mechatronic design methodology that follows the CE approach.

During the specification design, conceptual design, embodiment design and prototyping, all the disciplines must work together. It can be said that at these stages a mechatronics engineer must be present to coordinate the effort of different specialists. Only in the detailed design phase, can the work be done by individual teams.

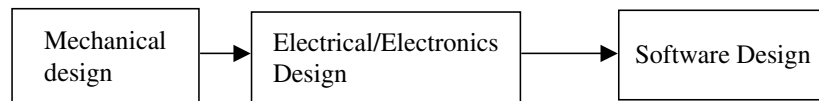


Figure 2.4. *Conventional design approach*

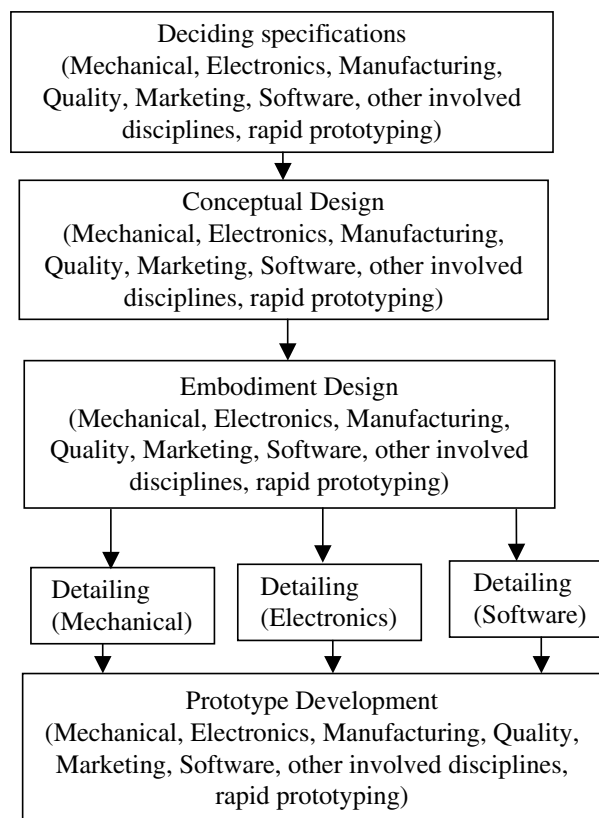


Figure 2.5. *A mechatronics design methodology*

Mechatronics students have to be trained in the philosophy of CE. Not only do the aspects of various disciplines have to be considered together, but also the manufacturing and marketing aspects have to be considered at the design stage itself. According to Brussel [BRU 96], mechatronics aims at a CE view on machine design.

Another feature of mechatronics education is that projects form a very important part of the education. There can be various miniprojects associated with courses. Finally, a major project can be carried out. The involvement of industry will help in defining the projects and in completing them successfully.

2.8. Incorporating mechatronics in the course structure of undergraduate students

Nowadays, at many places in India and abroad, mechatronics is taught as a separate discipline. However, in this section, the main focus is on teaching mechatronics to mechanical engineering students. The teaching of mechatronics can be started from the first year itself. This has to be done without providing additional load on the students. By taking the Indian Institute of Technology Guwahati curriculum as an example, it will be discussed how mechatronics education can be incorporated in it.

Table 2.3 shows the course structure for the first year, which is the common course for all disciplines. The course Engineering Mechanics can be replaced by a course on Introduction to mechatronics based on the following three reasons:

- 1) Students carry out thorough preparation on mechanics for various entrance examinations for engineering. This gives them extra-confidence after they are selected for engineering. As a result, they neglect this course in their first year of engineering and end up with little learning.

2) The first-year curriculum is a common course. The students in Biotechnology, Chemical Science and Technology and Design may not be interested in learning Engineering Mechanics beyond their pre-engineering level.

3) Like other courses, engineering mechanics follows the bottom-up approach, which does not provide any thrill to students. A course on the Introduction to mechatronics is expected to be a sound remedy for the above-mentioned reason.

Semester 1	L-T-P-C	Semester 2	L-T-P-C
MA-101 Mathematics-I	3-1-0-8	MA-102 Mathematics-II	3-1-0-8
CH-101 Chemistry	3-1-0-8	ME-101 Engineering mechanics	3-1-0-8
CH-110 Chemistry laboratory	0-0-3-3	CS-101 Introduction to computing	3-1-0-6
PH-101 Physics-1	2-1-0-6	PH-102 Physics-II	2-1-0-6
ME-111 Engineering drawing	2-0-3-7	BT-101 Modern biology	3-1-0-8
ME-110 Workshop-I	0-0-3-3	EC-102 Basic electronics laboratory	0-0-4-4
EC-101 Electrical sciences	3-1-0-8	CS-110 Computing Laboratory	0-0-3-3
HS-1xx English/HSS elective	3-0-0-6	PH-110 Physics laboratory	0-0-3-3
NCC/NSS/NSO	0-0-0-0	NCC/NSS/NSO	0-0-0-0

Note: L – lecture hours per week, T – tutorial hours per week, P – practical hours per week and C – credit.

Table 2.3. *First-year course structure*

The introductory course on mechatronics will contain the following salient topics:

1) definition and scope of mechatronics with examples of mechatronics products with a brief description about their

working: mechatronics in automobiles, aircraft, machine tools, process industries, laboratory instruments and so on;

2) basic mechanisms;

3) comparison of various electric motors and hydraulic and pneumatic systems;

4) introduction to PLC; microprocessors, microcontrollers and computer control.

A top-down approach may be followed in teaching of the course. Each topic can take about 10 lectures. The tutorial hour may be used to show various toys and models to small group of students. This will motivate students across the disciplines.

Table 2.4 shows the second-year course structure. In the third semester, mechanical engineering students have to do a course on electrical engineering that includes a laboratory component. This course can be replaced by a middle-level course on mechatronics. Infrastructure and expertise of an institution may be the major factors in either modifying this course or totally replacing it. There is no scope to include any other course related to mechatronics. However, as the students have already done an introductory course on mechatronics, some examples from the mechatronics area can be chosen. For example, the course on solid mechanics can include some examples of stress analysis of electronic devices.

In the fourth semester, the Mechanical Engineering Laboratory course can include some experiments on mechatronics. These can be on hydraulic and pneumatic control systems. The course on Workshop can include some miniprojects related to mechatronics.

Semester 3	L-T-P-C	Semester 4	L-T-P-C
HS-2xx HSS elective	3-0-0-6	XX-2xx Science elective	3-0-0-6
MA-201 Mathematics-III	3-1-0-8	HS-2xx HSS elective	3-0-0-6
CS-201 Object oriented programming and data structures	3-0-3-9	ME-202 Engineering materials	3-0-0-6
ME-201 Solid mechanics	2-1-0-6	ME-203 Advanced solid mechanics	2-1-0-6
ME-204 Fluid mechanics-I	2-1-0-6	ME-205 Thermodynamics	3-1-0-8
EC-205 Introduction to electrical engineering	3-0-2-8	ME-206 Fluid mechanics-II	2-1-0-6
ME-211 Machine drawing	0-0-4-4	ME-210 Workshop-II	0-0-0-6
		ME-212 Mechanical engineering laboratory -I	0-0-4-4

Note: L – lecture hours per week, T – tutorial hours per week, P – practical hours per week and C – credit.

Table 2.4. *Second-year course structure*

Table 2.5 shows the third-year course structure. Here, there is a scope to include a bit of mechatronics in every course. The course on Manufacturing Technology-I can include the fabrication of chips and microstructures. The course on mechanical measurements should include a lot of items from electronics. Signal processing should also be taught on this course. The design of machine elements course can be modified to include a selection of motors and other items. The kinematics of machinery and heat and mass transfer course should include a number of examples across disciplines. The laboratory courses in both the semesters can include a significant portion of mechatronics. There is already a course on control systems. This can be transformed to a course on the control of mechatronics systems. The

course on machine design can include the design of mechatronics systems.

Semester 5	L-T-P-C	Semester 6	L-T-P-C
ME-301 Manufacturing technology-I	3-1-0-8	HS-3xx HSS elective	3-0-0-6
ME-302 Mechanical measurements	2-1-0-6	ME-306 Manufacturing technology-II	3-1-0-8
ME-303 Design of machine elements	3-1-0-8	ME-307 Machine design	3-0-2-8
ME-304 Kinematics of machinery	2-1-0-6	ME-308 Dynamics of machinery	2-1-0-6
ME-305 Heat and mass transfer	3-1-0-8	ME-309 Control systems	3-1-0-8
ME-310 Mechanical engineering laboratory-II	0-0-4-4	ME-311 Mechanical engineering laboratory-III	0-0-4-4
ME-321 Applied thermodynamics-I	2-1-0-6	ME-322 Applied thermodynamics-II	2-1-0-6

Note: L – lecture hours per week, T – tutorial hours per week, P – practical hours per week and C – credit.

Table 2.5. *Third-year course structure*

Table 2.6 shows the course structure for the final year (i.e. fourth year). In the seventh semester, one elective can be replaced by a compulsory course on mechatronics that can be a 2-0-2-6 type course, with two hours of lectures and two hours of practicals per week. As the basic experiments in mechatronics would be covered in laboratory courses, the laboratory in mechatronics course will essentially be for miniprojects.

In this way, mechatronics can be incorporated in the existing curriculum. The challenges are in motivating the faculty members to adapt to this change and in making available good textbooks and laboratory facilities.

Semester 7	L-T-P-C	Semester 8	L-T-P-C
ME-399 Summer training	PP/FF 0	HS-4xx HSS elective	3-0-0-6
XX-4xx Open elective-I	3-0-0-6	XX-4xx Open elective-II	3-0-0-6
ME-401 Industrial engineering operations research	3-1-0-8	ME-xxx Departmental elective-III	3-0-0-6
ME-xxx Departmental elective-I	3-0-0-6	ME-xxx Departmental elective-IV	3-0-0-6
ME-xxx Departmental elective-II	3-0-0-6	ME-499 Project-II	0-0-0-16
ME-411 Mechanical engineering laboratory-IV	0-0-4-4		
ME-498 Project-I	0-0-8-8		

Note: L – lecture hours per week, T – tutorial hours per week, P – practical hours per week and C – credit.

Table 2.6. *Fourth-year course structure*

2.9. Mechatronics for postgraduate students

Postgraduate students come from various backgrounds. Therefore, the course should start from basic level and go up to intermediate or advanced level. At the Indian Institute of Technology Guwahati, the course “Mechatronics and Manufacturing Automation” fulfils that requirement. The course syllabus is as follows:

Definition of mechatronics; mechatronics in manufacturing, products and design; Review of fundamentals of electronics; Data conversion devices, sensors, microprocessors, transducers, signal processing devices, relays, contactors and timers; Microprocessors, controllers and PLCs; drives: stepper motors, servo drives; Ball screws, linear motion bearings, cams, systems controlled by camshafts, electronic cams, indexing mechanisms, tool magazines and transfer systems; Hydraulic systems: flow, pressure and direction control valves, actuators and supporting elements, hydraulic power

packs and pumps; Design of hydraulic circuits; Pneumatics: production, distribution and conditioning of compressed air, system components and graphic representations, design of systems; Description of PID controllers; CNC machines and part programming; Industrial robotics.

The course has three lectures per week. The laboratory portion is supported by a course having a laboratory class of six hours per week. The syllabus of the course is as follows:

Measurement of cutting forces, surface roughness, tool wear, dimensional deviation and vibrations in machining; Measurement of chip thickness ratio and temperature in machining; Determination of the mill modulus of a laboratory rolling mill; Measurement of micro-hardness; ring compression test for the estimation of friction in metal forming; Open-die forging: observation of bulging and forging load; Hydraulic and pneumatic systems; Sensors and transducers; PID controller; Study of robots; CNC programming; Design of simple electronic circuits; Microprocessors and PLCs for manufacturing applications; Electrochemical machining, laser and plasma cutting; Vacuum coating.

In the above courses, the italicized portion is directly relevant to mechatronics.

At present, these courses are compulsory for the Computer-Assisted Manufacturing stream of M.Tech. and optional for other streams. A lot of training in mechatronics can be imparted through the M.Tech. thesis of the student.

2.10. Planning of a mechatronics program at postgraduate and undergraduate level

Several universities are now running a postgraduate program in mechatronics [ACA 97, SAL 03]. Some of them

are integrated programs of four-to-five years duration. Two-year programs usually admit students from mechanical and electrical or electronics background. The course structure differs from country-to-country and university-to-university. A thrust on laboratory components is an essential feature of a mechatronics program.

A typical postgraduate-level program consisting of four semesters can be divided into two semesters of course work and two semesters of a thesis related to mechatronics design and fabrication. A tentative course structure for the two semesters is provided in Table 2.7. The students of mechanical/production/industrial or electrical/electronics background can be admitted into the program. Some difference in the training of mechanical and electrical groups can be made by means of compulsory and elective courses.

At undergraduate level, the course should be a judicious mixture of mechanical, electrical, electronics and computer science. Many universities are offering the four-year undergraduate program in mechatronics and we can refer to their Web page for the course structure. Some references [ACA 97, SAL 03] also provide the undergraduate program structure. The following guidelines can be considered while designing a four-year program in mechatronics:

- 1) A top-down approach should be adopted. Initially, there should be some courses providing the overall exposure of mechatronics systems. This will motivate the students and help in a better grasping of the subject.

- 2) The laboratory component should be more than that of existing traditional engineering courses. It can be from 40% to 50%.

- 3) Miniprojects should be part of the course structure starting from second year to third year. A miniproject can be of one-semester duration. Thus, each student will be able to carry out a total of four miniprojects in the course duration.

4) There should be a final year project of one-year duration.

5) Some courses from the basic sciences and humanities should also be provided.

Course	Semester 1	Semester 2
Compulsory course-I	Mathematics including numerical methods and programming. The course can have three lectures per week and 2 h of programming laboratory.	Control of mechatronic systems. Preferably the course should have two lectures and one 2 h laboratory class each week and should include pneumatic, hydraulic control and fuzzy set-based control.
Compulsory course-II	Elements of mechanical engineering (for students of electrical or electronics background) or elements of electrical or electronics (for students of mechanical background). This course can have three lectures per week.	Design methodology for mechatronics product. Preferably 2 h of lectures and 2 h of laboratory work per week, where the students can work on miniprojects.
Compulsory course-III	Mechatronics laboratory providing exposure of mechatronic products, sensors, PLCs, microprocessor, hydraulic and pneumatic. The course should have two classes of 3 h duration each.	Advanced mechatronics. It can have three lectures per week and can include advanced topics in sensors, actuators and embedded systems.
Two elective courses in each semester	A number of elective courses can be floated depending on the expertise of the department and demand of the students. Examples: finite element modeling of mechatronic systems, optimization, soft computing, real-time computing systems, advanced digital signal processing, image processing, robotics, CAD-CAM, microprocessors, digital control system, advanced microelectronic circuits	

Table 2.7. *Tentative course structure for two-year MS program in mechatronics*

2.11. Some examples of mechatronics projects

Projects are a very important part of mechatronics education. The technology of mechatronics is rapidly changing and it is not possible to cope with these changes by textbook reading alone. By executing the project, the student gets familiar with many technological developments. At the same time, the project helps the student in understanding design, manufacturing, purchasing and the testing aspects of mechatronics. In this section, some projects carried out on the final year undergraduate and postgraduate programs of the Indian Institute of Technology Guwahati are briefly described to give an idea of the types of projects.

2.11.1. Design and fabrication of a mechatronic wheelchair

A joystick-operated mechatronic wheelchair was designed and fabricated at IIT Guwahati [DHA 02, KOD 03]. Two independent DC motors controlled by a pulse width modulation scheme run the two wheels of the wheelchair. Turning is accomplished by varying the speed of the motor. The salient feature of this project is that the design was modular and that it can be retrofitted to conventional wheelchairs. Due to PWM control, the energy efficiency was improved. Figure 2.6 shows the block diagram of the power module of the wheelchair. As a result of the project, students learned rehabilitation needs, mechanical design, ergonomics, aesthetics and electronics. Figure 2.7 shows the testing of the wheelchair. The project got publicity in local newspapers, which motivated the students and technicians involved in the project.

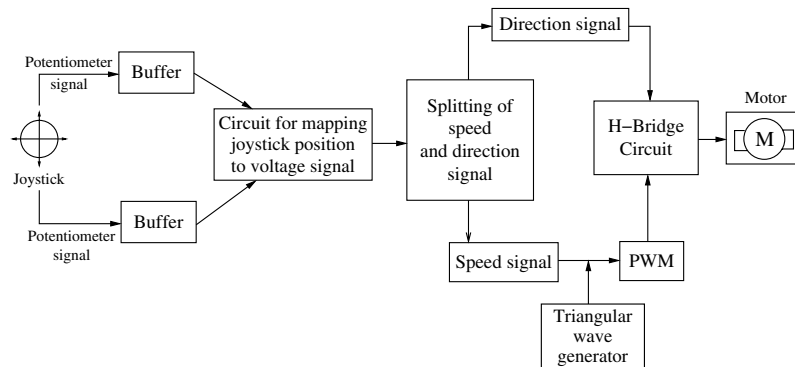


Figure 2.6. *Structure of a power module*



Figure 2.7. *Testing of a mechatronic wheelchair*

2.11.2. Automatic gear changing system for cars

In this project, an automatic gear changing system for cars was developed [RAJ 04]. The system is developed as a module that can be retrofitted to conventional cars. The feedback of engine speed and accelerator pedal position is

taken as input to cause x and y movement of the lever through rack and pinion drives. Based on a fuzzy logic program, a microcontroller actuates two motors to bring the gear-shifting lever into a particular position. During the gear shifting operation, the clutch paddle gets automatically disengaged. Figure 2.8 shows a prototype of the gear change module. In this project, the students learned about the fabrication of a rack and pinion drive and the operation of the microcontroller.

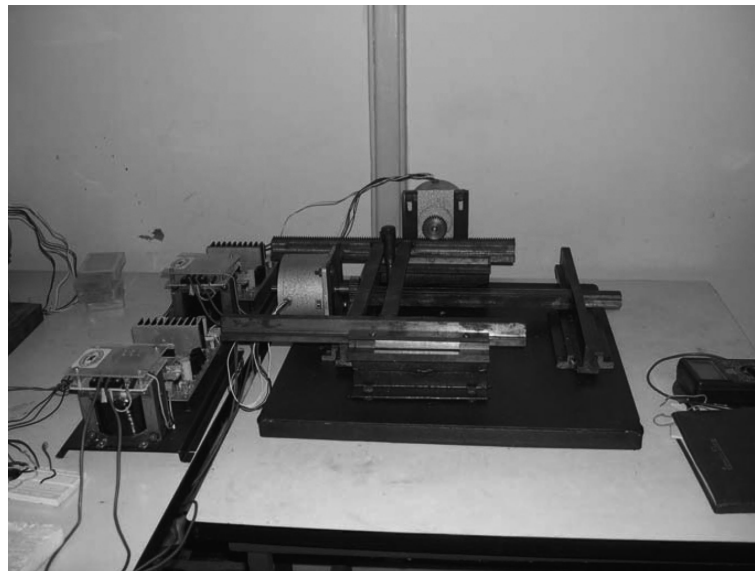


Figure 2.8. *Prototype of gear change module*

2.11.3. Design and fabrication of robots

A number of projects were about designing and fabricating specific types of robots. Initially, a three-axes Cartesian robot with magnetic gripper was developed [CHE 01]. This robot was controlled by a microprocessor. Later on, a PC-controlled, shop floor inspector robot (Figure 2.9) was developed [BAN 01]. This was a (four-axis and gripper) stepper

motor-driven robot. It has a digital vernier caliper, which can be used for measuring the dimensions of machined components. The inspection data can be stored in the PC. Thus, the robot was used for segregating good and defective parts. The cost of manufacturing this robot was around \$1,000 in 2001. This robot can also be used as an educational robot as it can carry out a variety of tasks and can be easily programmed using C language.

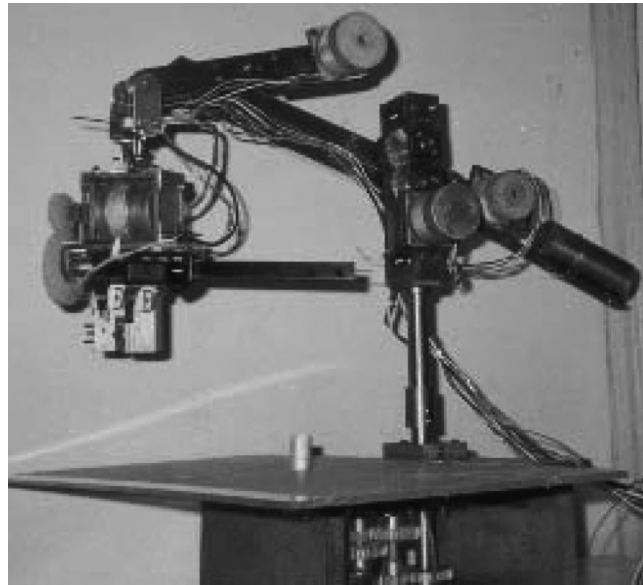


Figure 2.9. *Shop floor inspector robot developed in a B.Tech. project*

2.11.4. Design and fabrication of an electronic cam

A cam is used to convert rotary motion into a reciprocating motion. Depending on the characteristics of motion of the reciprocating follower, a cam (in the form of disk or drum) is fabricated with a particular profile. In the 19th and the first half of the 20th Century, cams were very popular in automatic machines. Even now, they are used at several places. One common example is the opening and

closing of inlet and exhaust valves of a four-stroke engine. The design and manufacturing of a cam is a tedious task and a new cam has to be used if the characteristics of motion changes.

It is possible to replace a cam and the follower system by a stepper or servo motor-based system. This was attempted in a B.Tech. project [RAW 02]. The rotary motion was converted into reciprocating motion by using a power screw and nut combination. The power screw was driven by a motor, which was programmed by a microprocessor and a nut acted as a follower.

2.12. Conclusion

In this chapter, various aspects of mechatronics education are described. There are two prominent ways of providing mechatronics education – by incorporating the mechatronics courses in the regular curriculum of mechanical engineering and by having a separate program of mechatronics. Both these modes of education are discussed. Mechatronics education has to follow a top-down approach and projects form a very important part of mechatronics education.

Two major challenges along with the possible measures to tackle them are as follows:

- 1) There is difficulty getting instructors for mechatronics education, as the discipline is very young and persons trained in mechatronics are scarce. Over a period of time, a sufficient number of trained mechatronics graduates will be available and instructor-related problems will be lessened. To tackle this problem for the time being, guest faculty members from other departments and industry can be hired.

- 2) Laboratories and projects form a very important component of mechatronics education. Limited resources in academic institutes may discourage the progress of

mechatronics education. One way to tackle this problem is to involve industries, which can fund the projects, in mechatronics education.

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Chapter 3

Mechatronics Educational System Using Multiple Mobile Robots with Behavior-Based Control Approach

A unique education system is proposed for students pursuing mechanical engineering to learn basic mechatronics skills and techniques practically. The system is composed of three subsystems. The first subsystem is used for second year students to learn mainly input/output port operations, periodically switching LED lights ON/OFF and a stepper motor control. The second subsystem is effective for third year students to learn AD conversion for several sensory information systems, DA conversion for a DC motor control and a design of a discrete-time PI controller. Further, the third subsystem is a system of multiple mobile robots – part of the graduation studies so that fourth year students can learn the concept of subsumption control architecture for schooling behavior.

Chapter written by Fusaomi NAGATA, Keigo WATANABE and Maki K. HABIB.

3.1. Introduction

Up to now, many studies on educational systems have been conducted. In this chapter, a unique mechatronics educational system is proposed for mechanical engineers, to enable them to efficiently learn basic skills and techniques of mechatronics. For this purpose, the C++ of Microsoft Visual Studio is recommended as a software development environment, because it is one of the languages with professional technical skills demanded by different industries. The developed educational system is composed of three subsystems. The first subsystem is used for second year students to learn input or output port operations using hexadecimal code, periodically switching light emitting diode (LED) lights ON or OFF by using a Windows timer, such as a sampling period of 10 ms and stepper motor control built in a position control module and a mobile robot with two wheels. The second subsystem is used for third year students to learn analog digital (AD) conversion supporting different analog sensory information, digital analog (DA) conversion for direct current (DC) motor control and proportional-integral-derivative (PID) control method. Further, the third subsystem consists of a system with multiple mobile robots supporting the final year graduation thesis study of fourth year students to learn the concept of subsumption architecture for swarm intelligence, such as schooling behavior. The effectiveness of the proposed systems is evaluated through experimental instructions at Tokyo University of Science, Yamaguchi, Japan.

3.2. Mechatronics education subsystem I

3.2.1. *Hardware of mechatronics educational subsystem I*

Figure 3.1 shows the first mechatronics system consisting of an LED display board, a position control device and a

mobile robot with two wheels [KIT 11, KIT 12]. The system is used in the experimental lecture of “Mechatronics Experiment I” for second year students. Figure 3.2 shows the block diagram of the LED display experiment. Sixteen LEDs are arrayed with two rows as shown in Figure 3.3 and each row is related to output port B and C, respectively. In Figure 3.3, hexadecimal number 0X55 and 0XAA are set to port B and port C, respectively. A lighting pattern can be designed by setting the necessary hexadecimal code number; also, a lighting period can be changed by using a Windows timer interrupt associated with a sample rate, such as, 10 ms.

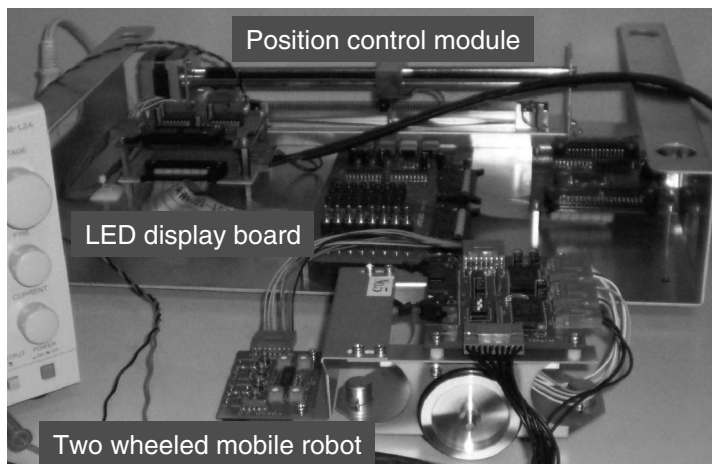


Figure 3.1. Mechatronics subsystem consists of LED display board, a position control device, and a mobile robot with two wheels, which is used in the experimental lecture of “Mechatronics Experiment I”



Figure 3.2. Block diagram of LED display experiment using universal serial bus (USB) interface

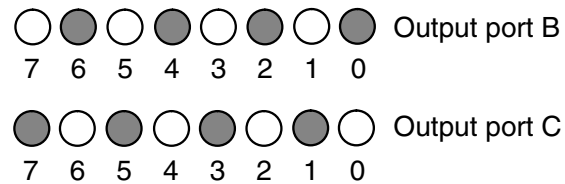


Figure 3.3. Relation between two-arrayed LEDs and output ports B and C

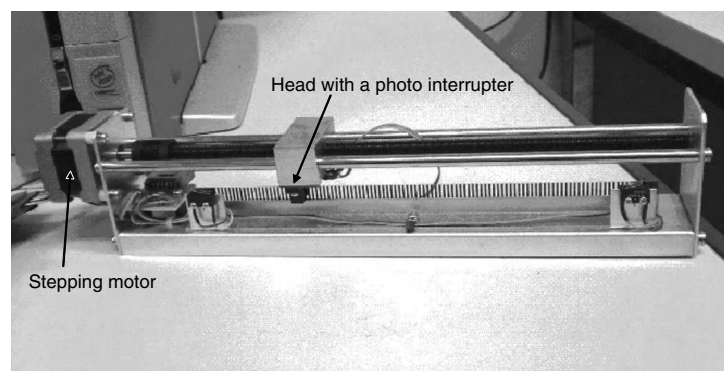


Figure 3.4. Position control device with a photo interrupter driven by a stepper motor

Figure 3.4 shows the position control device driven by a stepper motor. A moving head is integrated with a ball screw mechanism. A photo interrupter is attached to the moving head to detect the position of the slit while moving. The stepper motor is driven by pulse signals. One pulse signal rotates the stepper motor 1.8 degrees, and this moves the moving head by 6.25 μm through the ball screw mechanism. The pulse signal is generated by the lower four bits of output port B. The relation between the binary code number sent to port B and the type of motion is listed as follows:

- 1) 00000110 (0X06) Low-level code for clockwise rotation (CWL).
- 2) 00000111 (0X07) High-level code for clockwise rotation (CWH).

- 3) 00000010 (0X02) Low-level code for counterclockwise rotation (CCWL).
- 4) 00000011 (0X03) High-level code for counterclockwise rotation (CCWH).
- 5) 00001000 (0X08) Motor excitation off.

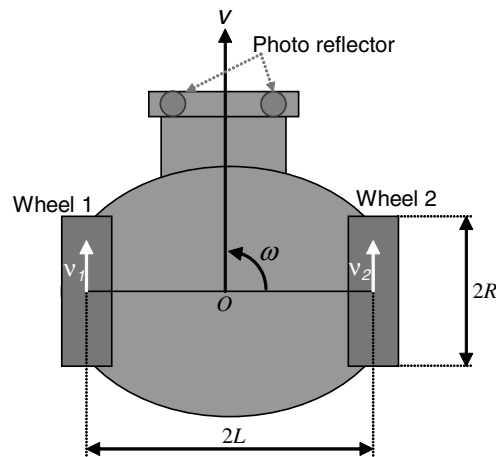


Figure 3.5. Top view of two-wheeled mobile robot with two photo reflectors

Figure 3.5 illustrates the mobile robot with two wheels and two photo reflectors. Wheels 1 and 2 are driven by stepper motors 1 and 2, respectively. The stepper motors 1 and 2 are excited by the lower four bits of output ports B and C, respectively. In Figure 3.5, v and ω are the translational velocity and the rotational velocity of the robot in the robot coordinate system; $2L$ is the distance between the two wheels and R is the radius of each wheel. The robot can perform forward and backward motions or rotational motion. When forward and backward motions are applied, the velocity of each wheel, v_1 , v_2 , is set as

$$v = v_1 = \omega_1 R = v_2 = -\omega_2 R \quad [3.1]$$

Also, when the rotational motion is conducted, the rotational velocity ω of the robot is given by

$$\omega = \frac{\omega_1 R}{L} = \frac{\omega_2 R}{L} \quad [3.2]$$

where ω_1 and ω_2 ($\omega_1 = \omega_2$) are the rotational velocities of two wheels, respectively.

3.2.2. Basic dialog for students' experiment

This section introduces the basic interactive window dialog developed for second year students' Mechatronics Experiment I. Students can effectively design a control program by using a dialog panel and learn basic mechatronical peripheral techniques. The Mechatronics Experiment I is considered for second year students at the department of mechanical engineering, which is composed of three topics, i.e. periodically switching LED lights ON or OFF experiments, a positioning experiment for position control and line tracing experiments of a two-wheeled mobile robot. As an example, Figure 3.6 shows the developed interactive window dialog designed for the line tracing experiment using the mobile robot stated in Mechatronics Experiment I. For example, if the "CW rotation of Motor 1's" button is clicked, then the stepper motor 1 rotates 1.8 degrees in the clockwise direction. Students can not only confirm the motion but also see the corresponding program codes in another window.

At first, the students learn how to program important basic functions such as moving forward or backward, turning left or right and sensing two photo reflectors through the dialog developed by using Microsoft Visual C#. Then, students can make a program for a line trace by making use of the basic functions. Fifteen hours (five hours, three days) are allotted to the Mechatronics Experiment I at Tokyo University of Science, Yamaguchi, Japan.

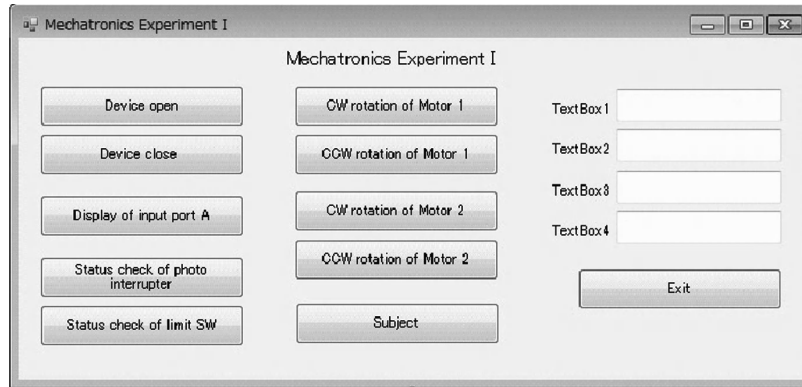


Figure 3.6. Windows dialog designed for Mechatronics Experiment I

3.3. Mechatronics educational subsystem II

3.3.1. *Hardware of mechatronics educational subsystem II*

Figure 3.7 shows the hardware of the second mechatronics system consisting of three sensors for measuring temperature, distance and brightness, AD/DA conversion interfaces, a liquid crystal display (LCD) display panel and a DC motor with a sensor of photo interrupter, which is provided by C-TASK Co., Ltd. The system is used in the experimental lecture of “Mechatronics Experiment II” for third year students [KIT 11, KIT 12].

Here, the basic software developed for velocity control of the DC motor is explained. A ladder-type DA converter is connected to output port 1, so that the voltage within the range from 0 to 3.3 V can have an output with the resolution of 256 steps. The velocity control of the DC motor can be performed by changing the voltage. The velocity of the motor is controlled by a simple proportional-integral (PI) action in the discrete time k given by

$$\tau(k+1) = \tau(k) + \Delta\tau(k) \quad [3.3]$$

$$\Delta\tau(k) = K_p \{v_d - v_s(k)\} + K_i \sum_{n=1}^k \{v_d - v_s(n)\} \quad [3.4]$$

where $\tau(k)$ is the output torque to the DC motor at the discrete time k ; n is the incremental counter to make the sum of error for integral action; K_p and K_i are the P-gain and I-gain, respectively; v_d is the reference value of rotational velocity; and $v_s(k)$ is the rotational velocity measured by using a photo interrupter shown in Figure 3.8. A rotational wheel with a small hole is fixed to the shaft of the DC motor. When the hole passes through the photo interrupter, the output signal of the photo interrupter is going through transition from high level to low level, and this signal is a pulse that can be detected and counted. The rotational velocity is defined as the counted number of pulses within a constant time period (sample time).

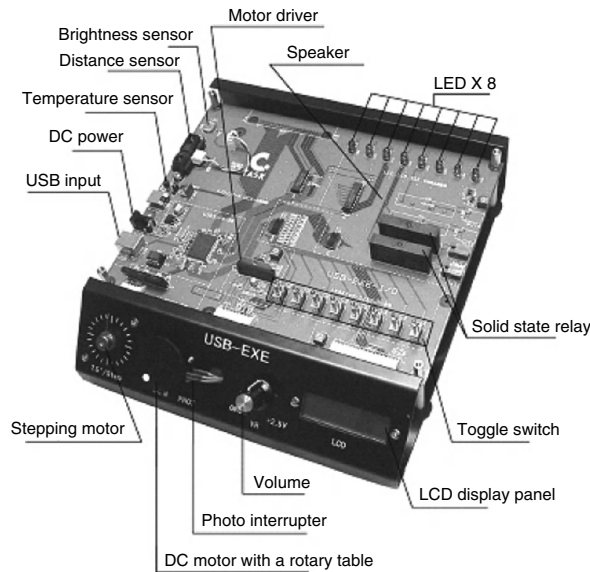


Figure 3.7. Mechatronics experiment system consisting of three sensors for measuring temperature, distance and brightness, AD/DA conversion interfaces, an LCD display panel and a DC motor with a photo interrupter

3.3.2. Basic dialog for students' experiment

A basic interactive window dialog was designed to support Mechatronics Experiments II. Students can efficiently make a control program by using the interactive window dialog and study basic mechatronical peripheral techniques concerning AD conversion of sensory information from analog sensors, pulse width modulation (PWM) control of a DC motor and PI control of rotational velocity. Mechatronics Experiment II is considered for third year students, which is mainly composed of three topics, i.e. AD conversion of several analog signals from sensors, such as distance, temperature and brightness, and DA conversion for velocity control of a DC motor. Students try to make a program for a discrete-time PI controller using equations [3.3] and [3.4] for controlling the velocity of the DC motor.

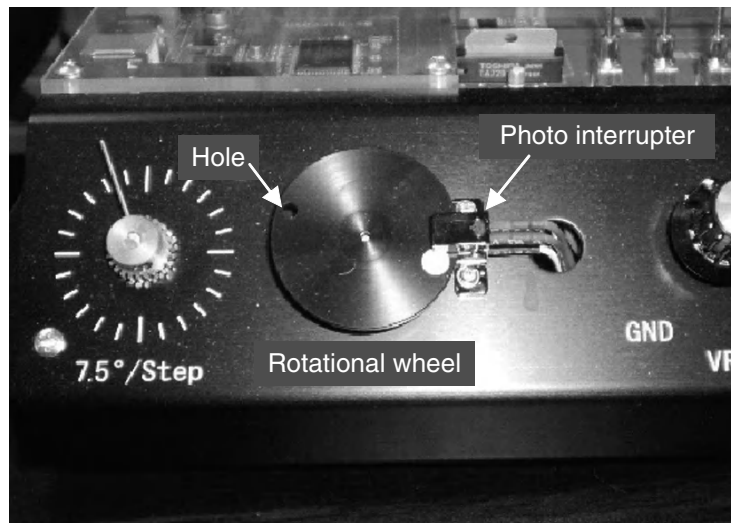


Figure 3.8. *Rotational wheel fixed to a DC motor with a sensor of photo interrupter*

Figure 3.9 shows the interactive window dialog designed for the purpose of the Mechatronics Experiment II. For

example, if the “Velocity control of the DC motor” button is clicked, then the DC motor rotates following the velocity set by “Reference” in the dialog. Students can not only confirm the motion of the DC motor but also see the corresponding control program codes in another window. Ten hours (five hours, two days) are allotted to the set of experiments under Mechatronics Experiment II.

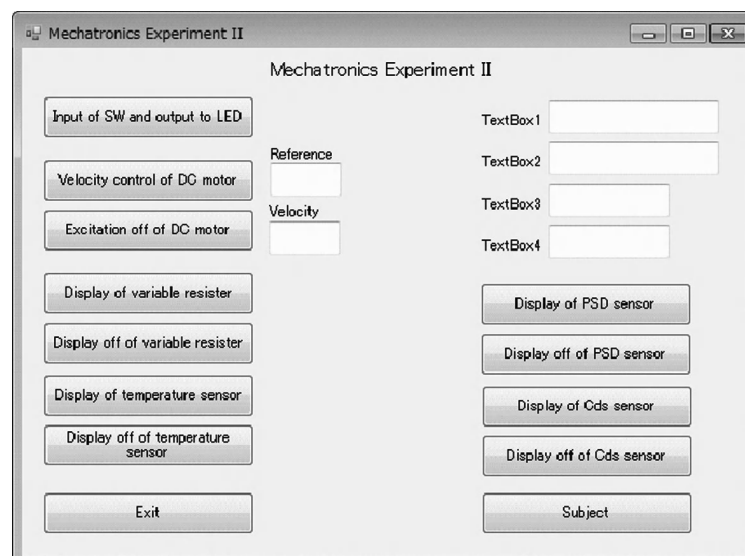


Figure 3.9. Windows dialog designed for Mechatronics Experiment II

3.4. Mechatronics educational subsystem III

This section includes a multiple mobile robots system integrated with subsumption control architecture to support final year study.

3.4.1. Mobile robot with three wheels

Students, who have gone through the lectures of Mechatronics Experiments I and II can easily cope with this

part to support their final year study needs in their fourth year. This section of experiments includes multiple mobile robots; each is equipped with six distance sensors as shown in Figure 3.10. These robots are used to demonstrate the emergence of schooling behavior. The integrated distance sensors for each robot are called position sensitive detector (PSD) sensors, which can measure the distance to an object. Six PSD sensors are equally fixed, 60 degrees from each other, around the boundary of each mobile robot as shown in Figures 3.10 and 11 [YAM 10, NAG 11, YAM 11].

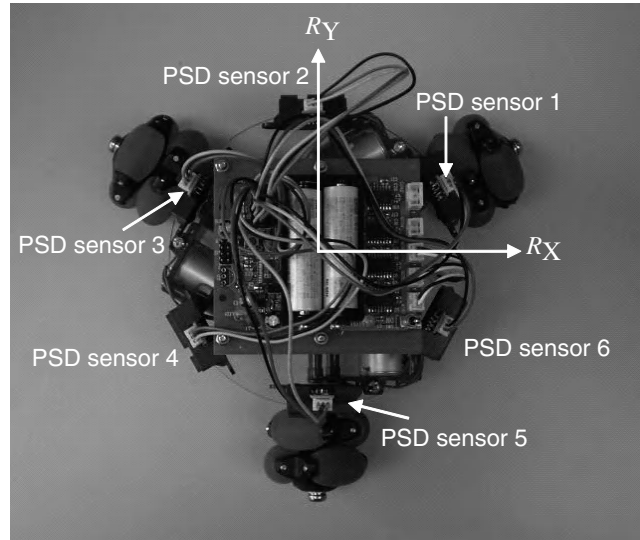


Figure 3.10. Mobile robot with three wheels and six PSD sensors

Next, the kinematic control method of the mobile robot is explained. Figure 3.12 illustrates the kinematic model of the robot. ω_i ($i = 1, 2, 3$) is the angular velocity of each wheel. Also, v_i ($i = 1, 2, 3$) is the velocity of each wheel and it is given by

$$v_i = r\omega_i \quad (i = 1, 2, 3) \quad [3.5]$$

where r is the radius of each wheel. If the position and orientation vector of the robot, i.e. the origin in the robot coordinate system $\sum_R (O-RX^RY)$, is given by $\mathbf{x}_r = [x_r \ y_r \ \phi_r]^T$, then the velocity can be represented by $\dot{\mathbf{x}}_r = [\dot{x}_r \ \dot{y}_r \ \dot{\phi}_r]^T$. The following kinematic equations are obtained from Figure 3.12 [WAT 98, TAN 99].

$$v_1 = -\frac{1}{2}\dot{x}_r + \frac{\sqrt{3}}{2}\dot{y}_r + L\dot{\phi}_r \quad [3.6]$$

$$v_2 = -\frac{1}{2}\dot{x}_r - \frac{\sqrt{3}}{2}\dot{y}_r + L\dot{\phi}_r \quad [3.7]$$

$$v_3 = \dot{x}_r + L\dot{\phi}_r \quad [3.8]$$

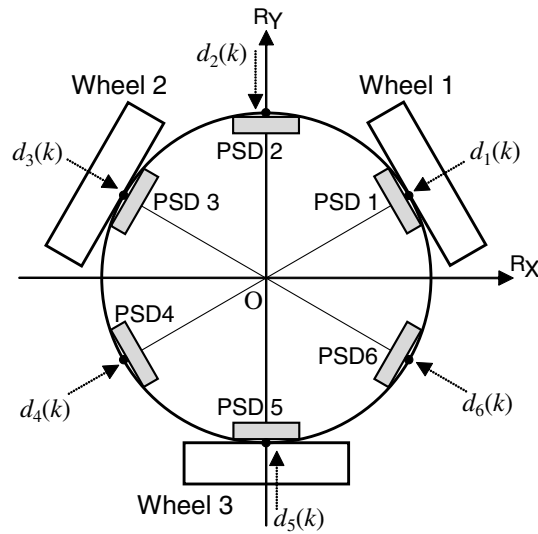


Figure 3.11. Positions of six PSD sensors fixed around a mobile robot

where L is the distance between the center of the robot and the center of each wheel. Equations [3.6] through to [3.8] lead to

$$\begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{pmatrix} = \frac{1}{r} \begin{pmatrix} -\frac{1}{2} & \frac{\sqrt{3}}{2} & L \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & L \\ 1 & 0 & L \end{pmatrix} \begin{pmatrix} \dot{x}_r \\ \dot{y}_r \\ \dot{\phi}_r \end{pmatrix} \quad [3.9]$$

By using equation [3.9], the robot can be controlled kinematically. As special cases, Table 3.1 shows the velocity components to move to the direction of each PSD sensor. When designing the schooling mode using multiple mobile robots, the six basic velocities in Table 3.1 are used. The important point is that the direction of velocity, a mobile robot generates in Σ_R , depends on the ratio $\dot{x}_{ri} : \dot{y}_{ri}$. If the ratio is kept as tabulated in Table 3.1, the velocity norm may be changed voluntarily.

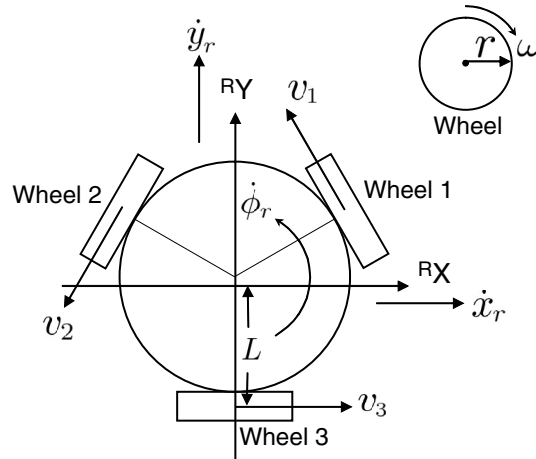


Figure 3.12. Kinematics of the mobile robot with three wheels

i	1	2	3	4	5	6
$\dot{x}_{ri}$	$\sqrt{3}$	0	$-\sqrt{3}$	$-\sqrt{3}$	0	$\sqrt{3}$
$\dot{y}_{ri}$	1	0	1	-1	-2	-1

Table 3.1. Velocity components to move to the direction of each PSD sensor, in which $i(i = 1, \dots, 6)$ denotes the number of PSD sensors

As mentioned above, the third Mechatronics educational subsystem is designed using multiple mobile robots, each having three wheels and six PSD sensors. This subsystem is used to support study needs of fourth year students, to learn the subsumption control architecture for schooling behavior. The subsumption control architecture is called behavior-based artificial intelligence, which was first proposed by Brooks [BRO 86]. Students can practically know the concept of the proposed subsumption control architecture for schooling behavior, which provides a method for structuring reactive systems from lower level to higher level, using layered sets of rules, i.e. reactive behaviors according to the change of a robot's environment. The details will be introduced in later sections.

3.4.2. Network-based multiple mobile robots system

A network-based multiple mobile robots system is proposed to design a high-level software architecture for multiple mobile robots using robot platforms with limited capabilities. Figure 3.13 shows the layout arrangement of the network-based multiple mobile robots system. Each robot can only transmit six examples of PSD sensory information $\mathbf{d}_i(k) = [d_{i1}(k) \dots d_{i6}(k)]^T$ to the supervisory server through Bluetooth communication. The subscript i denotes the identification number of a robot. The supervisory server returns a set of a simple behavior and a short execution

time, e.g. 200 ms to the corresponding robot. Eight kinds of simple reaction behaviors as tabulated in Table 3.2 are prepared for the mobile robots. When a set of a command code and an execution time is transmitted from the supervisory server to a mobile robot, the mobile robot conducts the motion exactly within the specified execution time. Three agents “Avoid objects,” “Turn to left or right” and “Move forward” to realize a schooling behavior are designed by using the basic instructions shown in Table 3.2.

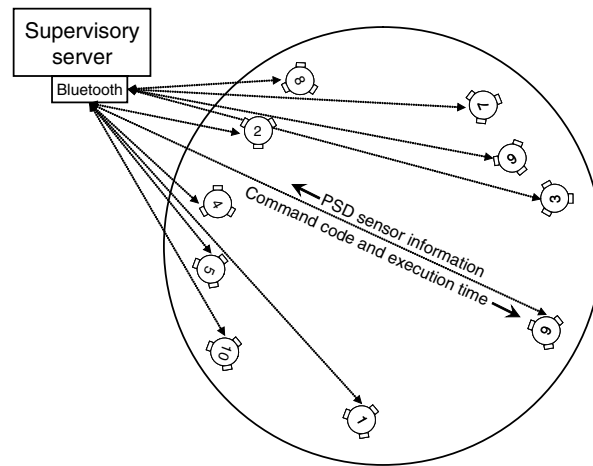


Figure 3.13. Network-based multiple mobile robots system aiming at the emergence of a schooling behavior

3.4.3. Subsumption control architecture implemented on supervisory server

The software development environment is C# of Windows Visual Studio, which is used to develop and implement high-level software architecture such as subsumption control architecture according to application requirements. Figure 3.14 shows an example of the subsumption control architecture implemented on the supervisory server. The

controller includes three agents: “Avoid objects”, “Turn to left or right” and “Move forward” for the schooling behavior of multiple mobile robots. The first agent has higher priority in terms of dispatch. This section introduces the three types of agents and the corresponding output command codes shown in Table 3.2. The eight commands shown in Table 3.2 are the most simply subdivided actions for the mobile robot.

Cmd. code	Corresponding motion
1	Move to the direction of PSD sensor 1
2	Move to the direction of PSD sensor 2
3	Move to the direction of PSD sensor 3
4	Move to the direction of PSD sensor 4
5	Move to the direction of PSD sensor 5
6	Move to the direction of PSD sensor 6
7	Rotate to clockwise direction
8	Rotate to counterclockwise direction

Table 3.2. Simple reaction behaviors for a mobile robot

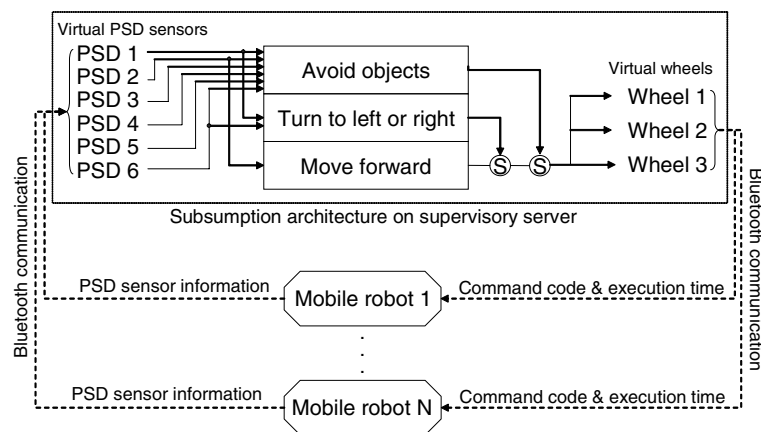


Figure 3.14. Subsumption control architecture for schooling behavior, which is implemented on supervisory server personal computer (PC)

The server receives PSD sensory information $d_i(k)$ ($1 \leq i \leq N$) from all mobile robots for every sampling period of 10 ms, in which N is the number of available mobile robots. By analyzing $d_i(k)$, the controller dispatches the current execution right to one of the three agents for the i th mobile robot. This process is periodically applied to all mobile robots in the order from 1 to N . In the schooling mode described in this section, all mobile robots try to regularly move along the inner area of a circular fence keeping a distance to both the fence and other mobile robots. This mode allows the robots to behave like carps in a Japanese artificial circular pond.

3.4.3.1. *Move forward*

When a robot moves counterclockwise along a circular fence as shown in Figure 3.13, the agent of “Move forward” is always active. Accordingly, if higher priority agents such as “Turn to left or right” and “Avoid objects” are inactive, then the agent “Move forward” can have the execution right and the following control law is applied.

$$\dot{\mathbf{x}}_i = v \frac{\dot{\mathbf{x}}_{i2}}{\|\dot{\mathbf{x}}_{i2}\|} \quad [3.10]$$

where $\dot{\mathbf{x}}_i = [\dot{x}_i \ \dot{y}_i]^T$ is the virtual translational velocity for the i th mobile robot and $\dot{\mathbf{x}}_{i2} = [0 \ 1]^T$ is the normalized velocity vector for moving to PSD sensor 2. The position of PSD sensor 2 is assumed to be the front of the mobile robot. v is the scalar signifying the magnitude of velocity. While the agent “Move forward” has the execution right, a set of a command code 2 and an execute time T , e.g. 200 ms, are continuously transmitted to the mobile robot within every specified execution time.

3.4.3.2. Turn to left or right

In this case, the orientation of a mobile robot is controlled by the agent “Turn to left or right”. This agent becomes active when $d_{i1}(k) < d_{\text{ref}}$ and $d_{i6}(k) < d_{\text{ref}}$ are simultaneously satisfied. d_{ref} is called the active reference range. Further, if this agent has the execution right, then the following control law is applied.

$$\dot{\varphi}_i = K_{\varphi} \{d_{i6}(k) - d_{i1}(k)\} \quad [3.11]$$

where $\dot{\varphi}_i$ is the virtual rotational velocity of i th mobile robot, $d_{i1}(k)$ and $d_{i6}(k)$ are the values of PSD sensors 1 and 6 transmitted from the i th mobile robot, respectively. As can be seen from Figure 3.11, PSD sensors 1 and 6 are selected for the orientation control moving in the counterclockwise direction. K_{φ} is the gain that can control the orientation of the robot to be parallel to the inner side of the circular fence. In this case, a set of a command code 7 or 8 and an execution time T are continuously transmitted to the i th mobile robot for every specified execution time. The command code 7 or 8 is determined by the sign of $\dot{\varphi}_i$. The agent “Turn to left or right” has a higher priority than “Move forward”. Thus, while the agent “Turn to left or right” has the execution right, then the agent “Move forward” is suppressed, i.e. blocked.

3.4.3.3. Avoid objects

The agent “Avoid objects” has the highest priority. When $\exists d_{ij}(k) [d_{ij}(k) < d_d]$ becomes true, then this agent becomes active, i.e. has the execution right at the same time. After becoming active, this agent generates the virtual velocity given by

$$\dot{\mathbf{x}}_i = -v \frac{\dot{\mathbf{x}}_{ij}}{\|\dot{\mathbf{x}}_{ij}\|} \{d_d - \min_j d_{ij}(k)\} \quad \{\exists d_{ij}(k) [d_{ij}(k) < d_d]\} \quad [3.12]$$

where d_d is the minimum desired limit distance between a robot and an object or obstacle. The supervisory server transmits a set of command codes $j + 3$ (in case of $j = 1, 2$ or 3) or $j - 3$ (in case of $j = 4, 5$ or 6) and an execution time T to a mobile robot to avoid a collision with the nearest robot or object. Due to the activation of the “Avoid objects” agent, the mobile robot can move away from moving objects, including other mobile robots within the collision critical zone. If the distance to the nearest object is smaller than d_d , the robot tries to expand the distance to be d_d . When multiple PSD sensors simultaneously detect shorter distances than d_d , the mobile robot tries to preferentially move away from the nearest object.

Figure 3.15 shows an experimental scene of schooling behavior, in which multiple mobile robots are controlled based on the subsumption control architecture incorporated in the supervisory server as shown in Figure 3.14. It was confirmed from the experiments that the multiple mobile robots could perform a desirable schooling behavior.

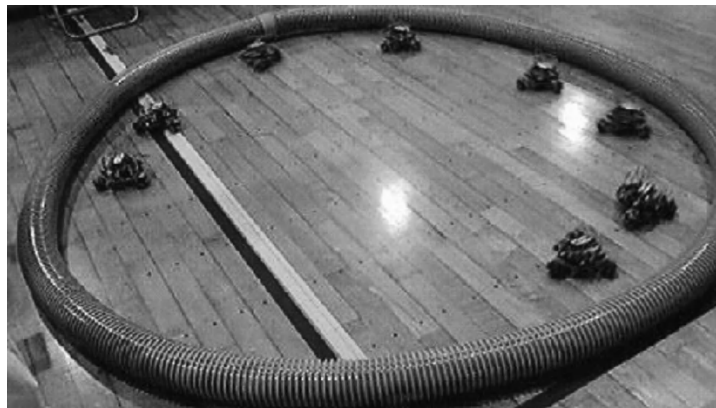


Figure 3.15. *An experiment of schooling behavior based on the proposed network-based subsumption architecture*

3.4.4. *Agent dispatcher*

The agent dispatcher supervises the controller shown in Figure 3.14. The dispatcher does not immediately move the execution right to a higher priority agent when a lower priority agent is running, because each agent works as a simple reactive behavior for every sampling period, according to sensory information. Instead of this, whenever a reaction behavior is executed during a specified execution time, the dispatcher updates the activity of each agent and gives the execution right to an updated active agent with the highest priority.

3.4.5. *Multiple sensory sensors*

The mobile robot introduced in this chapter basically has six AD conversion channels, all of which, however are already connected to six PSD sensors. To deal with sensory information from other sensors such as temperature, humidity, and force, a compact AD conversion module AGB65-ADC provided by Asakusagiken Co., Ltd. is mounted on the mobile robot. The AGB65-ADC has an AD converter that can deal with 16 analog channels. Figure 3.16 illustrates the block diagram showing the connection scheme within a mobile robot: sensors, an AGB65-ADC module and a Bluetooth module called Bluemaster.

The mobile robot has one serial port for data communication, so that text codes can be transmitted to and received from the Bluetooth module through AGB65-BT to the serial port 2 in AGB65-ADC. The Bluetooth module is used to communicate with the supervisory server PC. It should be noted that when communicating with the AD converter in AGB65-ADC to obtain the sensor's information through serial port 1, command sequence including a hexadecimal header code "0Xff" must be transmitted. In other words, the redirectable serial port on a AGB65-ADC

board can switch data to serial port 1 or serial port 2 automatically, which is the important redirect function of AGB65-ADC. Using the AD conversion module AGB65-ADC, students can easily add other types of sensory sensors further to the six PSD sensors to a mobile robot.

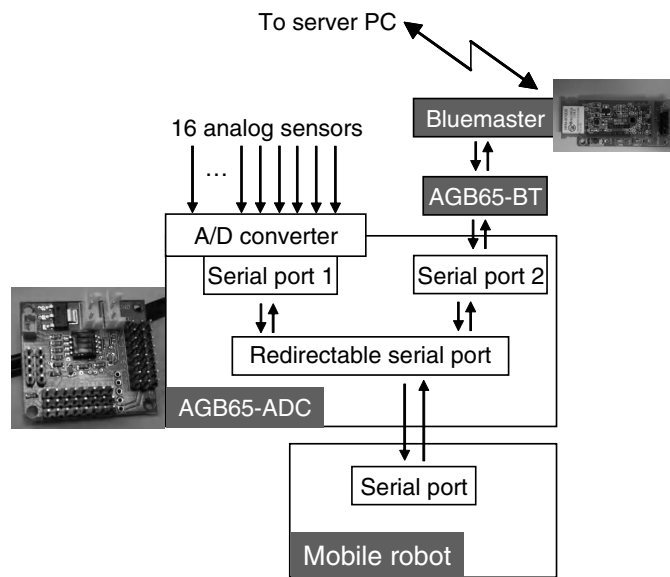


Figure 3.16. Compact AD conversion module ADC65 with 16 channels

3.5. Conclusions

In this chapter, a unique education system has been proposed for students pursuing mechanical engineering to learn basic mechatronics skills and techniques practically. The system is composed of three subsystems. The first subsystem is used for second year students to learn mainly input or output port operations, periodically switching LED lights ON or OFF, and a stepper motor control. The second subsystem is effective for third year students to learn AD conversion for several sensory information systems, DA

conversion for DC motor control and a design of a discrete-time PI controller. Further, the third subsystem is a system of multiple mobile robots (as one of graduation studies) so that the fourth year students can learn the concept of subsumption control architecture for schooling behavior. The effectiveness of the proposed mechatronics education systems has been evaluated through experimental instructions at Tokyo University of Science, Yamaguchi, Japan.

3.6. Bibliography

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Chapter 4

Knowledge Transfer between University and Industry: Development of a Vision Measuring System

This chapter discusses the transfer of knowledge between university and industry, and has the potential to benefit both partners, in designing innovative solutions, in the optimal allocation of resources, in motivating the students for new challenging tasks and finally in integrating multidisciplinary University/Industry teams.

The case study presented here is related to the field of industrial maintenance, concerning the measuring and monitoring of the railroad wheel profiles by the Portuguese railway company, Comboios Portugal (CP).

A vision system to measure the wearing of the wheels of a train moving at a slow speed of 5 km/h is studied here. A 1:1 scale static prototype is developed and the calibration and testing procedures are presented.

Chapter written by João M.G. FIGUEIREDO.

The developed prototype is based on an image processing system to provide for the automatic measurement of the moving wheels. The wheel's profile is acquired by the illumination of the wheel through a secant horizontal light plane. The profile's image is processed by identifying the line of the greatest light gradient in the whole image. The gradient's profile is then converted to the wheel's radial profile by means of a coordinate transformation model, which transforms the image plane into the wheel's radial plane.

Experimental results are presented and discussed in the following sections.

4.1. Introduction

Metrology is mainly concerned with the study of measuring instruments or methods and the treatment of the measurement results. The research and development of new measurement devices and procedures conducive to smaller uncertainties is a permanent challenge to the innovative skills of the metrologist.

The measurement of the railroad wheel's profile is a basic procedure in the regular maintenance of trains.

Railroad wheels have to be inspected over regular time intervals to evaluate the wearing out of the rolling surface. Wheels that have excessive wearing face a very high risk of jumping off the rails, causing a serious train accident.

Depending on the physical characteristics of the railroad and on the train's average velocity, there are different wearing profiles. Each wearing profile characterizes the correspondent railroad line. The physical factors such as the train velocity, the amplitude of the railroad curves, the number of curves to the left and to the right and so on

influence the wearing of the wheel's profile. Figure 4.1 shows a standard profile and a wasted profile of a wheel.

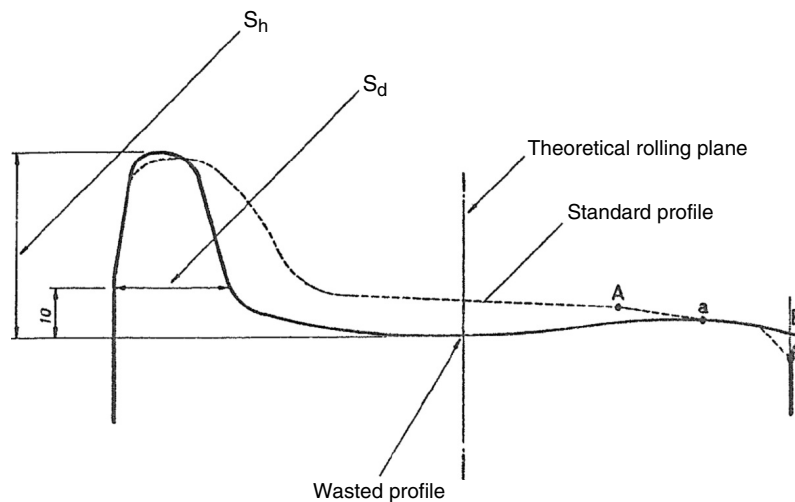


Figure 4.1. *Standard and wasted wheel's profile*

Manual measuring devices based on the well-known sliding caliper are the usual methods to evaluate the profile's dimensional characteristics, as shown in Figure 4.2.

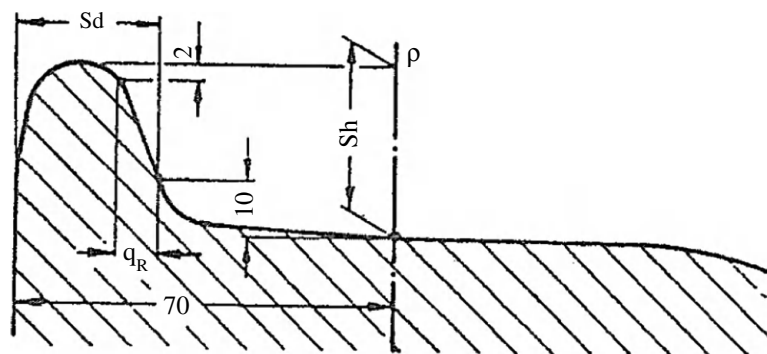


Figure 4.2. *Controlled dimensions of a wheel's profile*

Figure 4.3 shows a usual mechanical measuring device used in the Portuguese national railways company.

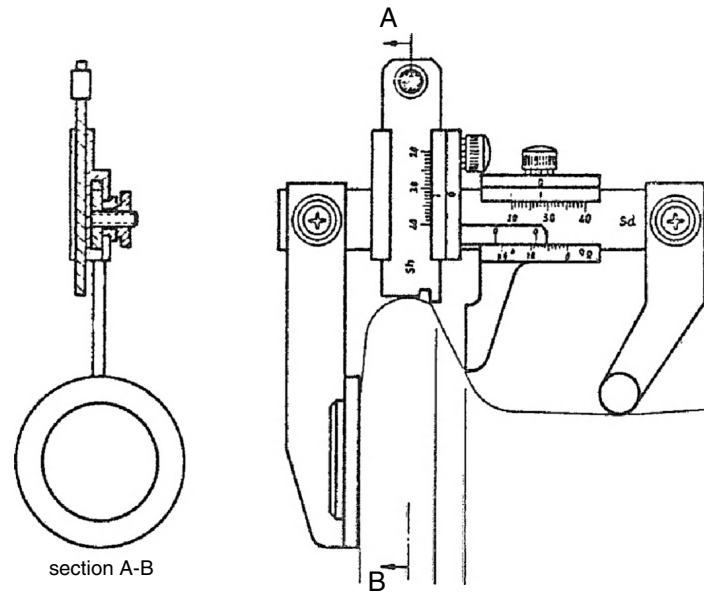


Figure 4.3. *Standard mechanical measuring device to measure the wheel's profile*

In this chapter, a vision system to measure the wearing of the wheels of a train moving at a slow speed of 5 km/h is developed. This new measuring method presents several advantages in relation to the usual standard manual methods, which are listed as follows:

- It is automatic and assures the correct saving of all measured data.
- The train does not need to stop to perform the measurement of all train wheels.
- It is very fast compared to the usual manual methods.
- It evaluates not only a few controlled dimensions of the profile but also the total profile.

Image processing technology is a very interesting solution in industry environments when a quick, accurate and traceable measurement has to be performed.

Image processing measurement systems are very useful in the manufacturing industry of components, verifying physical attributes (dimensions, color, etc.), the relative position of parts in subassembly sets, manufacturer labels and so on.

Artificial vision and image processing already have an important role in several technological domains as (1) pattern recognition, with multiple applications in industrial quality control [DU 08, GRI 08, KIM 10, ZHA 10, ZHA 12], medical diagnosis [GOU 07, BRO 10], face detection [GRI 09, PAI 10] and geometry restoration [HLO 03, LIM 11, CHE 12]; (2) visual servoing [NEL 03]; and (3) object tracking and movement detection [ALE 98, LEE 06, GRI 07, CUI 08, MES 10, YAN 10].

Among the different movement detection methods, there are two main processing methods: *interframe differencing* and *reference frame differencing*. The performance of both methods is drastically influenced by the pixel area where the method is applied and the subsequent use of the obtained results. These processing results are usually used in real-time monitoring [FAT 95] and video compression applications [JAI 81, MIT 96].

In the *interframe differencing method* [JAI 95], performance is defined for each pixel (x, y) between the frame obtained at instant t_1 (t_1 -frame) and the frame obtained at instant t_2 (t_2 -frame):

$$Dp(x, y) = \begin{cases} 1, & |F(x, y, t_1) - F(x, y, t_2)| \geq \tau \\ 0, & \text{otherwise} \end{cases} \quad [4.1]$$

where $Dp(x, y)$ is the difference in the intensity level of the pixel (x, y) and τ represents the threshold in the number of different pixels.

In the *reference frame differencing method* [JAI 95], performance is defined for each pixel (x, y) between the reference frame F_r and the t_n frame:

$$Dp(x, y) = \begin{cases} 1, & |F_r(x, y, t_r) - F(x, y, t_n)| \geq \tau \\ 0, & \text{otherwise} \end{cases} \quad [4.2]$$

where t_r and t_n represent the instants where the frames F_r and F_n were acquired, respectively.

The vision system to measure the wearing of a train's wheel moving at a slow speed of 5 km/h is studied through the development of a static 1:1 scale prototype in which calibration and testing procedures are presented. The developed prototype is based on an image processing system to provide for the automatic measurement of moving railroad wheels. The wheel's profile is acquired by the illumination of the wheel through a secant and horizontal light plane. This profile's image is processed by identifying the line of the greatest light gradient in the whole image. This gradient profile is then converted into the wheel radial profile by means of a coordinate transformation model, which transforms the image plane into the wheel's radial plane.

4.2. Measuring system

The developed measuring system comprises the following parts:

- light plane secant to the wheel;
- vision system (camera and image processing system);

- sensors to activate or deactivate the vision system;
- operator panel to display the results.

Figure 4.4 shows the system concept with the integration of all major components.

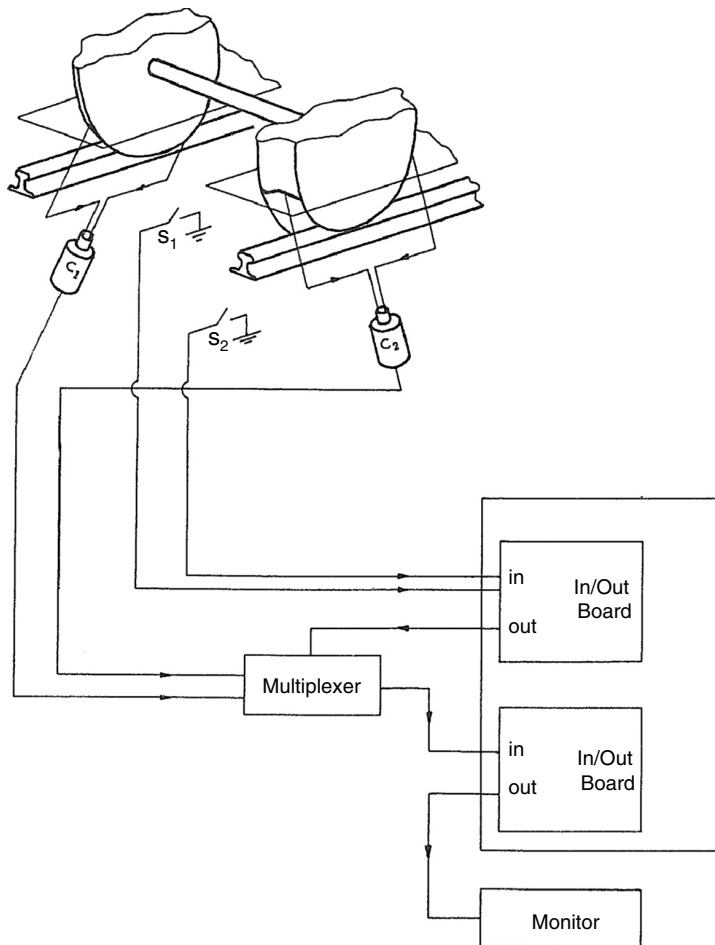


Figure 4.4. *System concept*

4.2.1. Light plane

The proper identification of the wheel's profile in the captured image is very important for an accurate measurement. Figure 4.5 illustrates the schematic hardware implementation to obtain the projected light plane, secant to the wheel.

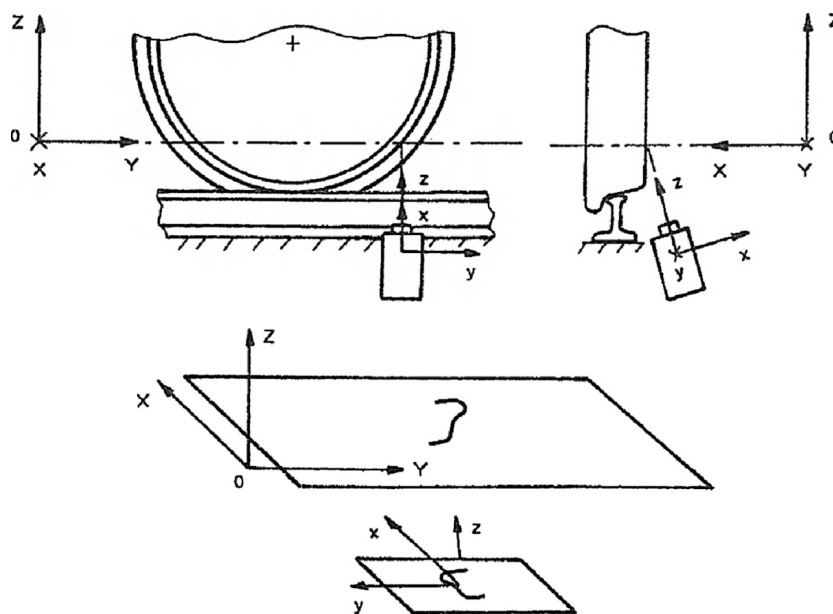


Figure 4.5. Hardware composition to obtain the light plane XOY secant to the wheel

Due to the fact that the measurement should occur on a train moving at a maximal speed of 5 km/h, even with a fast acquisition camera, the acquired profile is distorted due to the displacement of the wheel. To compensate for the previously mentioned distortion, a dual profile acquisition system was implemented through a mirror's composition, to maintain the line distance between two relative light profiles. Figure 4.6 illustrates the implemented system.

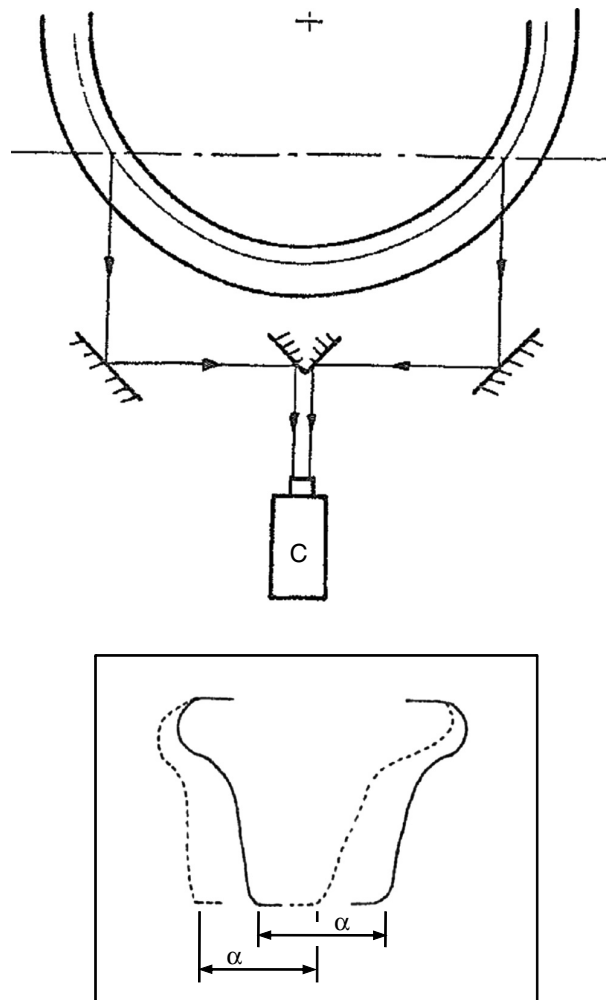


Figure 4.6. *Dual profile at image plane*

Figure 4.7 illustrates the distortion of a wheel's profile caused by the image acquisition of a moving wheel.

The advantages of the dual system are as follows:

- Two light profiles are acquired with only one video camera.

- The processing time is reduced by half.
- The knowledge of the two image profiles allows the calculation of the rolling diameter (as it will be later illustrated in Figure 4.13).
- Two corresponding points in the same image diameter are obtained almost simultaneously.

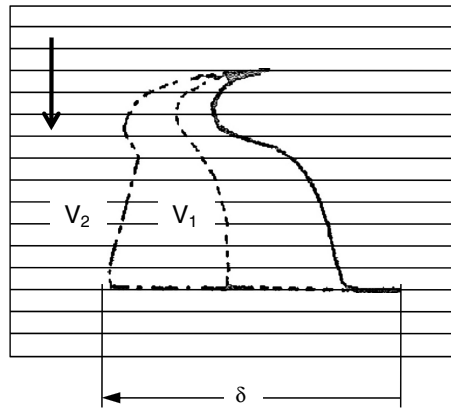


Figure 4.7. Distortion of the wheel's profile caused by a moving wheel with velocities V_1 and V_2 ($V_1 < V_2$)

4.2.2. Mathematical model

The measurement of physical dimensions through image processing techniques must, at first, be able to relate 3D points to 2D images [GON 87]. This perspective transformation is illustrated in Figure 4.8, and it can be implemented as stated in equation [4.3].

$$\begin{bmatrix} c_{h1} \\ c_{h2} \\ c_{h3} \\ c_{h4} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -1/\lambda & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad [4.3]$$

where:

$(c_{h1}, c_{h2}, c_{h3}, c_{h4})$ are homogeneous coordinates in the image plane;

(X, Y, Z) are space coordinates; and

λ is the camera focal distance.

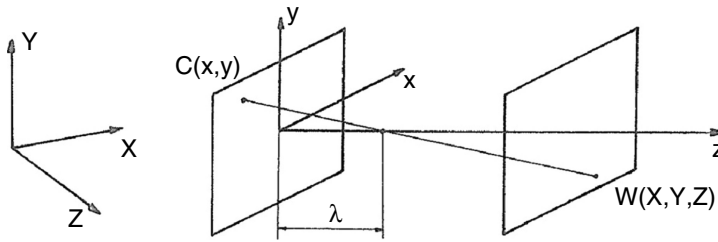


Figure 4.8. *Perspective transformation*

The relationship between the image homogeneous coordinates and the image Cartesian coordinates are

$$[x] = \left[\frac{c_{h1}}{c_{h4}} \right] \quad [4.4]$$

$$[y] = \left[\frac{c_{h2}}{c_{h4}} \right] \quad [4.5]$$

$$[z] = \left[\frac{c_{h3}}{c_{h4}} \right] \quad [4.6]$$

Substituting the above equations, we obtain the image Cartesian coordinates (x, y) :

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \frac{\lambda X}{\lambda - Z} \\ \frac{\lambda Y}{\lambda - Z} \end{bmatrix} \quad [4.7]$$

where:

(x, y) are coordinates in the image plane;

(X, Y, Z) are space coordinates;

λ is the camera focal distance.

In the case studied in this chapter, as the physical points to be measured belong to a plane (light plane), the developed model relates the position of a point in the light plane to its correspondent position in the camera's image plane. Figure 4.9 shows the relative position of the two planes (light plane and image plane).

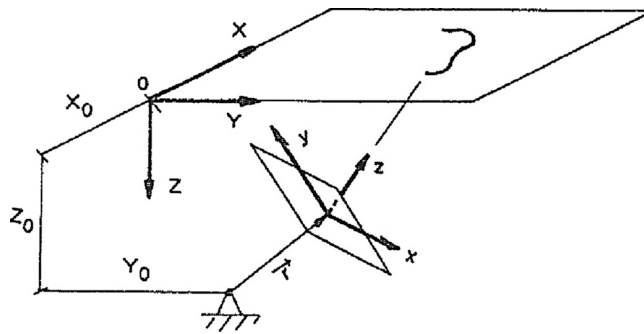


Figure 4.9. *Relative position of the light plane and the image plane*

A transformation model is needed to relate the two planes. This transformation can be implemented considering six degrees of freedom: three displacements (X, Y, Z) and three rotations (α, β, θ). A possible sequence of mathematical transformations applied to the camera's referential to place the image plane coincident to an arbitrary space plane can be obtained by [FIG 08]:

- 1) displacement of the camera fixation point from the origin to the final point $(X_0, Y_0, Z_0) - G$;
- 2) rotation of the x -axis by α degrees – $R(x, \alpha)$;

- 3) rotation of the y -axis by β degrees – $R(y, \beta)$;
- 4) rotation of the z -axis by θ degrees – $R(z, \theta)$; and
- 5) displacement of the image plane from the camera fixation point, $\vec{r}(r_1, r_2, r_3) - S$.

The aforementioned transformation sequence can be implemented using equations [4.8], where the transformation matrices are listed in equations [4.9]–[4.14].

$$C_h = P.S.R(z, \theta).R(y, \beta).R(x, \alpha).G.W_h \quad [4.8]$$

where:

C_h is an homogeneous coordinate in the image plane;

W_h is an homogeneous coordinate of a space point;

$P, S, R(z, \theta), R(y, \beta), R(x, \alpha), G$ are the transformation matrices.

$$G = \begin{bmatrix} 1 & 0 & 0 & -X_0 \\ 0 & 1 & 0 & -Y_0 \\ 0 & 0 & 1 & -Z_0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad [4.9]$$

$$R(x, \alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \alpha & \sin \alpha & 0 \\ 0 & -\sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad [4.10]$$

$$R(y, \beta) = \begin{bmatrix} \cos \beta & 0 & -\sin \beta & 0 \\ 0 & 1 & 0 & 0 \\ \sin \beta & 0 & \cos \alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad [4.11]$$

$$R(z, \theta) = \begin{bmatrix} \cos \theta & \sin \theta & 0 & 0 \\ -\sin \theta & \cos \theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad [4.12]$$

$$S = \begin{bmatrix} 1 & 0 & 0 & -r_1 \\ 0 & 1 & 0 & -r_2 \\ 0 & 0 & 1 & -r_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad [4.13]$$

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -1/\lambda & 1 \end{bmatrix} \quad [4.14]$$

According to this transformation sequence, we obtain the explicit model that relates the image plane to an arbitrary light plane located in the space [FIG 08]:

$$x = \lambda \frac{N_1(X - X_0) + N_2(Y - Y_0) + N_3(Z - Z_0) - r_1}{-D_1(X - X_0) + D_2(Y - Y_0) + D_3(Z - Z_0) + r_3 + \lambda} \quad [4.15]$$

$$y = \lambda \frac{N_4(X - X_0) + N_5(Y - Y_0) + N_6(Z - Z_0) - r_2}{-D_1(X - X_0) + D_2(Y - Y_0) + D_3(Z - Z_0) + r_3 + \lambda} \quad [4.16]$$

where:

$$N_1 = \cos \beta \cos \theta$$

$$N_2 = \sin \alpha \sin \beta \cos \beta + \sin \alpha \sin \theta$$

$$N_3 = \sin \alpha \sin \theta - \cos \alpha \sin \beta \cos \theta$$

$$N_4 = \cos \beta \sin \theta$$

$$N_5 = \cos \alpha \cos \theta - \sin \alpha \sin \beta \sin \theta$$

$$N_6 = \cos\alpha \sin\beta \sin\theta + \sin\alpha \cos\theta$$

$$D_1 = \sin\beta$$

$$D_2 = \sin\alpha \cos\beta$$

$$D_3 = \cos\alpha \cos\beta$$

(X, Y, Z) = spatial location of a point W in the global referential;

(X_0, Y_0, Z_0) = spatial location of the camera fixation point in the global referential;

(x, y) = location of the image point C , corresponding to the spatial point W , in the camera referential.

This model, however, does not solve our problem of reconstruction of the reality from the image knowledge. In fact, this model performs exactly the opposite. From the knowledge of the spatial location of a point $W(X, Y, Z)$, it calculates its correspondent location on the image plane $C(x, y)$, knowing all external parameters $(X_0, Y_0, Z_0, \alpha, \beta, \theta, r_1, r_2, r_3, \lambda)$.

The reconstruction of the reality implies the inverse solution of equations [4.15] and [4.16], which can be achieved by the following transformation:

$$W_h = G^{-1} . R^{-1}(x, \alpha) . R^{-1}(y, \beta) . R^{-1}(z, \theta) . S^{-1} . P^{-1} . C_h \quad [4.17]$$

The solution of this problem is not unique because there is an infinite number of solutions satisfying both equations [4.15] and [4.16], where all the collinear points with the camera image $C(x_1, y_1)$ and the camera focus are obtained. Therefore, we have to fix the space coordinate Z to obtain a unique solution. In our case, as we have all the points to measure in the same plane (light plane) this restriction has no negative consequences.

Hence, the inverse solution of equations [4.15] and [4.16] can be obtained for a specified Z , in a closed form, as follows [FIG 08]:

$$X = \frac{Q_1x + Q_2y + Q_3}{Q_4x + Q_5y + Q_6} \quad [4.18]$$

$$Y = \frac{Q_7x + Q_8y + Q_9}{Q_4x + Q_5y + Q_6} \quad [4.19]$$

where:

$$Q_1 = \cos\beta \cos\theta + O_1P_1$$

$$Q_2 = -\sin\theta \cos\beta + O_1P_2$$

$$Q_3 = O_1P_3 + O_2$$

$$Q_4 = \frac{P_1}{\lambda}$$

$$Q_5 = \frac{P_2}{\lambda}$$

$$Q_6 = \frac{P_3}{\lambda} + 1$$

$$Q_7 = \sin\theta \cos\alpha + \cos\theta \sin\beta \sin\alpha + O_3P_1$$

$$Q_8 = \cos\theta \cos\alpha - \sin\theta \sin\beta \sin\alpha + O_3P_2$$

$$Q_9 = O_3P_3 + O_4$$

$$P_1 = \frac{(\sin\theta \sin\alpha - \cos\theta \sin\beta \cos\alpha)}{Z/\lambda - O_5}$$

$$P_2 = \frac{(\cos\theta \sin\alpha + \sin\theta \sin\beta \cos\alpha)}{Z/\lambda - O_5}$$

$$P_3 = \frac{O_6 - Z}{Z/\lambda - O_5}$$

$$\begin{aligned}
O_1 &= \left(\frac{r_1}{\lambda} \cos \theta - \frac{r_2}{\lambda} \sin \theta \right) \cos \beta + \left(1 + \frac{r_3}{\lambda} \right) \sin \beta + \frac{X_0}{\lambda} \\
O_2 &= (r_1 \cos \theta - r_2 \sin \theta) \cos \beta + \left(\frac{r_1}{\lambda} \cos \theta - \frac{r_2}{\lambda} \sin \theta \right) \sin \beta + X_0 \\
O_3 &= \left(\frac{r_1}{\lambda} \sin \theta + \frac{r_2}{\lambda} \cos \theta \right) \cos \alpha \\
&\quad - \left(\left(\frac{r_2}{\lambda} \sin \theta - \frac{r_1}{\lambda} \cos \theta \right) \sin \beta + \left(1 + \frac{r_3}{\lambda} \right) \cos \beta \right) \sin \alpha + \frac{Y_0}{\lambda} \\
O_4 &= (r_1 \sin \theta + r_2 \cos \theta) \cos \alpha \\
&\quad - ((r_2 \sin \theta - r_1 \cos \theta) \sin \beta + r_3 \cos \beta) \sin \alpha + Y_0 \\
O_5 &= \left(\frac{r_1}{\lambda} \sin \theta + \frac{r_2}{\lambda} \cos \theta \right) \sin \alpha \\
&\quad + \left(\left(\frac{r_2}{\lambda} \sin \theta - \frac{r_1}{\lambda} \cos \theta \right) \sin \beta + \left(1 + \frac{r_3}{\lambda} \right) \cos \beta \right) \cos \alpha + \frac{Z_0}{\lambda} \\
O_6 &= (r_1 \sin \theta + r_2 \cos \theta) \sin \alpha \\
&\quad + ((r_2 \sin \theta - r_1 \cos \theta) \sin \beta + r_3 \cos \beta) \cos \alpha + Z_0
\end{aligned}$$

4.2.3. System calibration

The reconstruction of the actual geometry can be performed through the solution of equations [4.18] and [4.19], which implies the knowledge of several physical parameters, namely X_0 , Y_0 , Z_0 , x , y , α , β , θ , r_1 , r_2 , r_3 , λ and Z . Although, these parameters are possible to measure, their accuracy is determinant for the quality of the system measurements. Therefore, we have developed an automatic calibration method that enables us to calculate these parameters automatically, knowing the exact spatial position of a finite number of points in space and their correspondent localization in the image plane.

Rewriting equations [4.15] and [4.16], we can obtain the following nonlinear equations:

$$\begin{aligned} x \left(-(X - X_0) \sin \beta + (Y - Y_0) \sin \alpha \cos \beta - (Z - Z_0) \cos \alpha \cos \beta + r_3 + \lambda \right) \\ - \lambda \left((X - X_0) \cos \beta \cos \theta + (Y - Y_0) (\sin \alpha \sin \beta \cos \theta + \cos \alpha + \sin \theta) \right. \\ \left. + (Z - Z_0) (\sin \alpha \sin \theta - \cos \alpha \sin \beta \cos \theta) + r_1 \right) = 0 \end{aligned} \quad [4.20]$$

$$\begin{aligned} y \left(-(X - X_0) \sin \beta + (Y - Y_0) \sin \alpha \cos \beta - (Z - Z_0) \cos \alpha \cos \beta + r_3 + \lambda \right) \\ + \lambda \left((X - X_0) \cos \beta \sin \theta - (Y - Y_0) (\cos \alpha \cos \theta - \sin \alpha \sin \beta \sin \theta) \right. \\ \left. - (Z - Z_0) (\cos \alpha \sin \beta \sin \theta + \sin \alpha \cos \theta) + r_2 \right) = 0 \end{aligned} \quad [4.21]$$

Analyzing equations [4.15] and [4.16], we recognize that knowing the spatial location of a point (X,Y,Z) and its correspondent image location (x, y), we have as system unknowns, the variables $X_0, Y_0, Z_0, \alpha, \beta, \theta, r_1, r_2, r_3$ and λ .

Knowing that the maximal number of spatial independent equations that we can generate corresponds to three non-collinear points (six equations) (see [GON 87]), we have to reduce the number of unknowns to six.

The parameters r_1, r_2, r_3 and λ do not change with the camera position as these values are the camera manufacturer's parameters. Therefore, we can fix these parameters through accurate measurements in a laboratory. It follows that the set of unknowns is now reduced to six: $X_0, Y_0, Z_0, \alpha, \beta$ and θ . These six unknowns are automatically calculated with the knowledge of three non-collinear points in space and their correspondent localization in the image plane.

Newton-Raphson method is the numerical method used to solve the correspondent set of nonlinear equations [4.20] and [4.21] [CON 81].

Figure 4.10 shows the reference image to calibrate the system and the test image to determine the accuracy of the performed calibration.

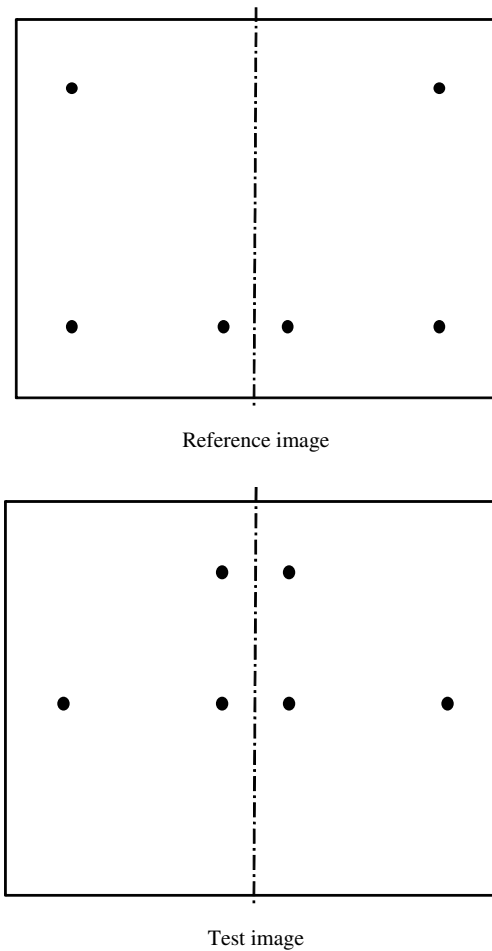


Figure 4.10. *Reference and test images*

4.3. Image processing algorithm

The illumination conditions are of major importance in simplifying a general algorithm for image processing.

In the present case, the illumination conditions were set in a specific way so that the obtained image can be binary processed. Only two levels of pixels were defined:

- white pixels – value $> K$ (predefined parameter);
- black pixels – value $< K$.

To elaborate the search algorithm, two major additional parameters were defined:

- initial search position;
- search directions for black–white transitions.

The main search criterion for the identification of a pixel belonging to the light profile is defined as follows:

- when the tested pixel is “black”, the next pixel to be tested is the adjacent pixel, following the search direction;
- when the tested pixel is “white”, the transition pixel is found and a new initial search position is defined.

The algorithm defined above, to process the profile’s image, is illustrated in Figure 4.11. Analyzing Figure 4.11, the search algorithm begins with the identification of points 1 and 2, following the vertical search directions n_1 and n_2 . Then, point x is identified and the search direction changes to the horizontal axis.

4.4. Results

4.4.1. *Building the wheel’s profile in the horizontal light plane*

From the knowledge of the image’s dual profile (Figure 4.11), we reconstruct the static wheel’s profile according to equation [4.22] as is illustrated in Figure 4.12:

$$y_i = (y_{\text{ref}_i} - y_{\text{comp}_i} - \text{CDROL}) / 2 \quad [4.22]$$

where:

y_{ref} is coordinate of the forward profile;

y_{comp} is coordinate of the backward profile;

CDROL is circumference's horizontal chord correspondent to the theoretic rolling diameter (see Figures 4.1 and 4.2).

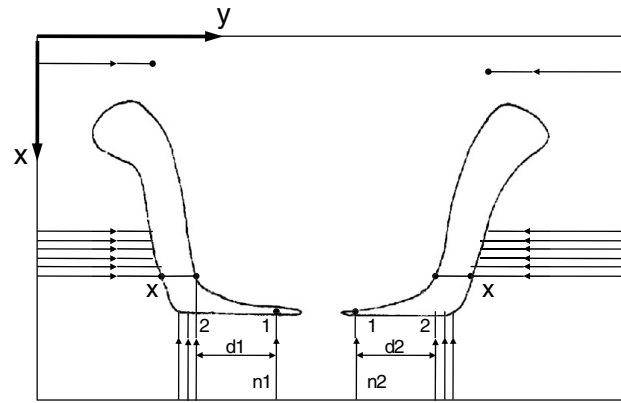


Figure 4.11. Image processing algorithm

Knowing the value of CDROL, also previously referred to in equation [4.22] and Figures 4.12 and 4.13, and ALT, the height of the light plane secant to the wheel, illustrated in Figure 4.13, the calculation of the wheel's diameter can be carried out as indicated in Figure 4.13, using equation [4.23].

$$\text{DIAM} = \frac{\text{CDROL}^2 + \text{ALT}^2}{\text{ALT}} \quad [4.23]$$

where:

DIAM is the wheel's diameter correspondent to the circumference's horizontal chord CDROL;

CDROL is the circumference's horizontal chord correspondent to the theoretic rolling diameter;

ALT is the height of the light plane secant to the wheel.

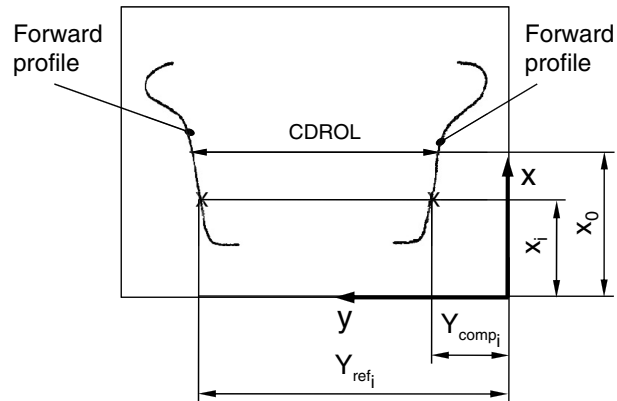


Figure 4.12. *Reconstruction of the static wheel's profile*

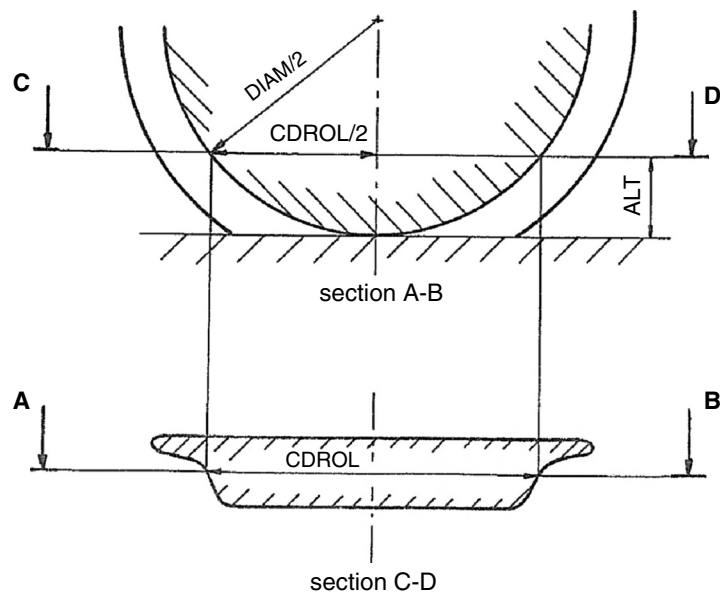


Figure 4.13. *Calculation of the wheel's diameter*

4.4.2. Building the wheel's profile in the radial plane

Knowing the wheel's profile in the horizontal light plane, we have to project this profile in the radial plane as shown in Figure 4.14.

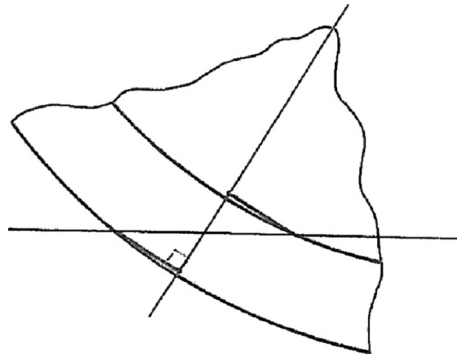


Figure 4.14. *Projection of the horizontal wheel's profile in the radial plane*

Intersection of the horizontal light plane with the wheel's radial plane results in the line r , which is parallel to the wheel's axis, as illustrated in Figure 4.15. This line intersects the wheel's radial profile in the theoretical rolling point, P , as indicated in Figure 4.15 and previously referred to in Figures 4.1 and 4.2.

Having defined the theoretical rolling diameter, the wheel's radial profile is divided into two zones, as illustrated in Figure 4.16:

- zone I: diameters smaller than the theoretical rolling diameter;
- zone II: diameters greater than the theoretical rolling diameter.

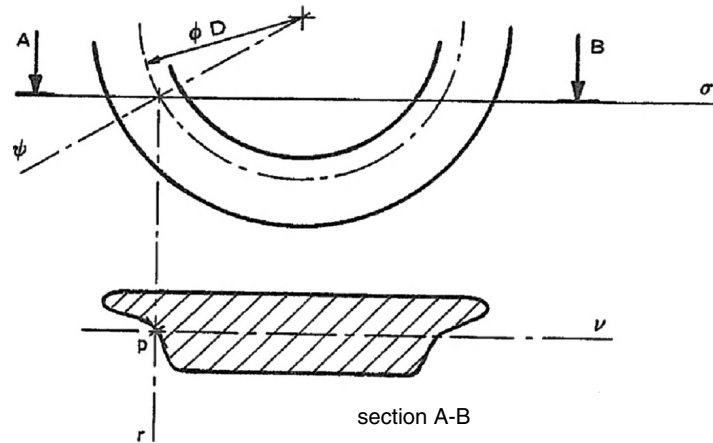


Figure 4.15. Intersection of the horizontal light profile with the wheel's radial profile (definition of the theoretical rolling point P)

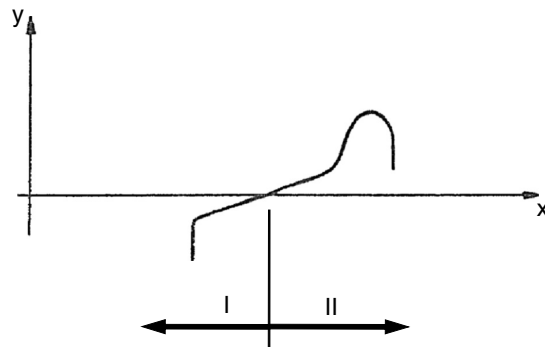


Figure 4.16. Two main zones of the wheel's radial profile regarding the theoretical rolling diameter

Finally, the wheel's profile in the axial plane can be built for both the zones I and II, according to the following equations (equations [4.24] and [4.25]) and using Figure 4.17:

$$R_I = -\left(ROL - \sqrt{(AUX2 - H_I)^2 + AUX1}\right) \quad [4.24]$$

$$R_{II} = \sqrt{(AUX2 - H_{II})^2 + AUX1} - ROL \quad [4.25]$$

where:

$$AUX1 = (ROL - ALT)^2 \quad [4.26]$$

$$AUX2 = \sqrt{(ROL^2 - AUX1)} \quad [4.27]$$

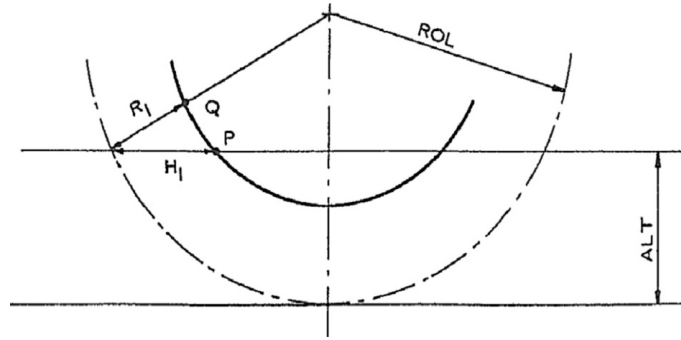


Figure 4.17. Transformation of the horizontal plane into the radial plane (ex: zone I)

4.4.3. Experimental results

The results shown in this section correspond to the actual measurements performed on a prototype. Figure 4.18 shows the built prototype. The light plane is shown in Figure 4.19.

Figure 4.20 shows the experimental image plane and Figure 4.21 shows the identified dual wheel's profile.

As can be seen from the analysis of Figure 4.20, the light reflection on the wheel's profile causes significant noise in the acquired image. However, this major disturbance being

filtered in the image's processing algorithm and being located in a region where the needed measurements are not affected (see Figure 4.1), it does not influence the quality of the measured data, such as rolling diameter, S_h and S_d , (quantities defined in Figure 4.1).

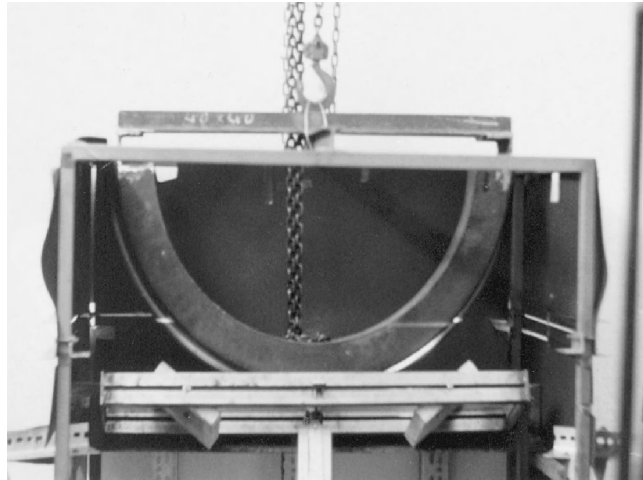


Figure 4.18. *Built prototype*

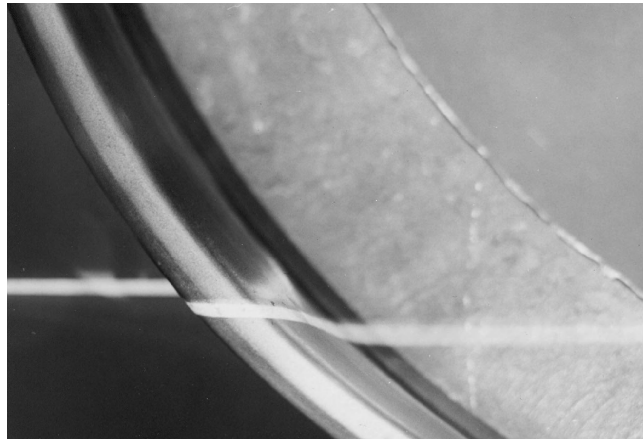


Figure 4.19. *Intersection of the light plane – wheel*

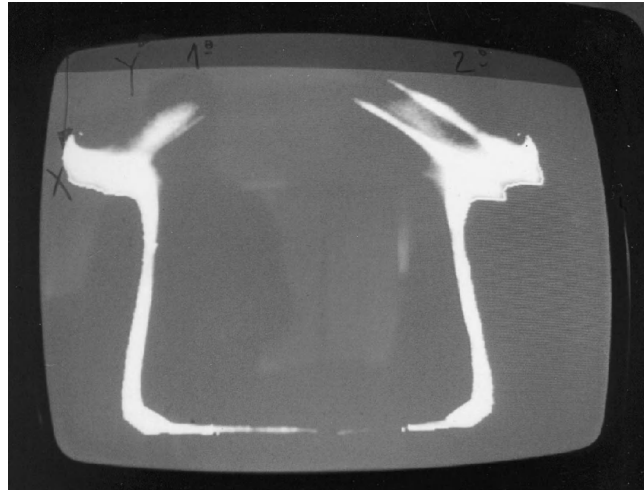


Figure 4.20. *Image plane*

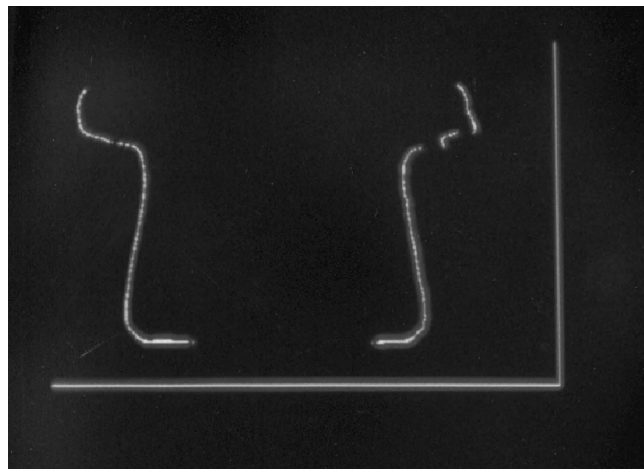


Figure 4.21. *Identified dual wheel's profile*

Table 4.1 shows the results from an experimental measurement made on the prototype, where we were able to reconstruct the reality with a maximal error value that is

less than 0.1 mm. The wheel's measured parameters refer to Figure 4.2.

Dimensional parameters	Actual values [mm]	Meas. values [mm]	Abs. error [mm]	Rel. error [%]
Theor. rolling diameter	860,000	860,073	-0.073	-0.01%
S_h	24,562	24,550	0.012	0.05%
S_d	35,803	35,799	0.004	0.01%

Table 4.1. *Prototype's measurement results*

Finally, Figure 4.22 shows the wheel's radial profile together with the automatic measured data, as shown to the operator.

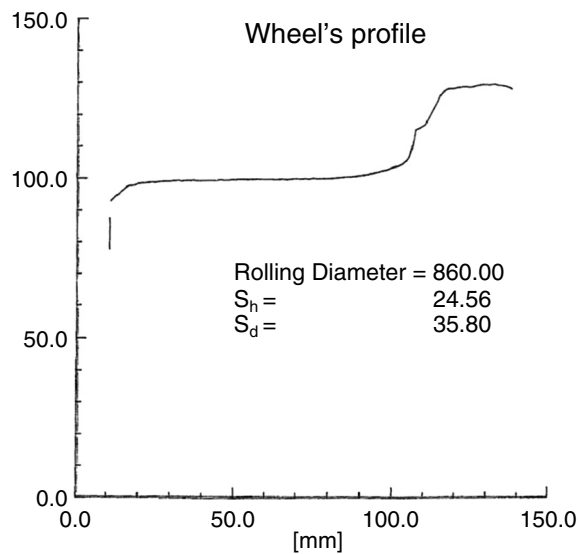


Figure 4.22. *Measured wheel's profile*

4.5. Conclusions

This chapter describes a successful example of cooperation between university and industry.

The case study presented here is related to the field of industrial maintenance, concerning the measuring and monitoring of the railroad wheel profiles in the Portuguese railway company, CP – Comboios Portugal. A vision system to measure the wearing of the wheels of a train moving at a slow speed of 5 km/h is developed.

A static 1:1 scale prototype is developed and the calibration and testing procedures are presented. The developed prototype is based on an image processing system to provide for the automatic measurement of moving railroad wheels. The wheel's profile is acquired by the illumination of the wheel through a secant and horizontal light plane. This profile's image is processed by identifying the line of the greatest light gradient in the whole image. This gradient profile is then converted into the wheel's radial profile by means of a coordinate transformation model, which transforms the image plane into the wheel's radial plane.

The results correspond to actual measurements carried out on a prototype. Significant noise was observed in the acquired image due to the high light reflection on the wheel's profile. However, this major disturbance being filtered in the image's processing algorithm and being located in a region where the needed measurements are not affected, it does not influence the quality of the measured data.

The measurements show very good accuracy, with relative errors below 0.1%.

4.6. Acknowledgment

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